MRR 2003-4

New Nouveau
Brunswick

Natural Resources
Minerals, Policy and Planning

Mineral Resource Report

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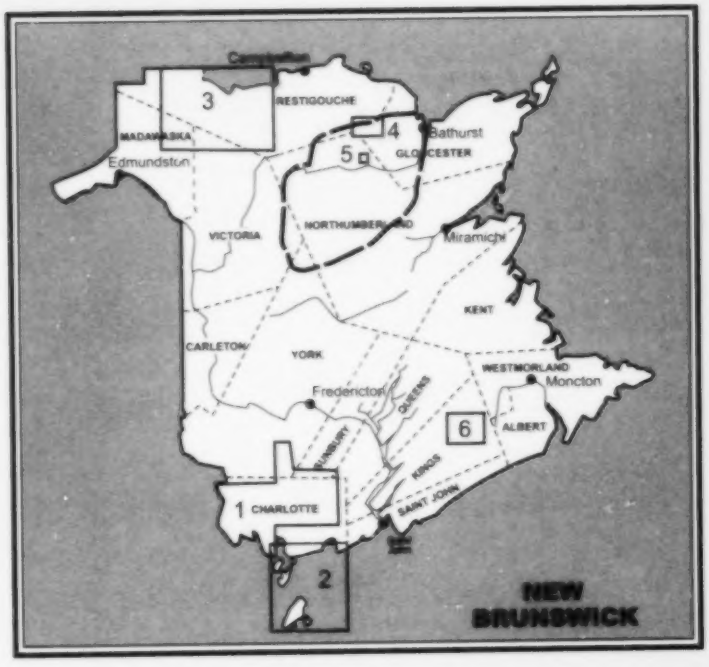

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Barbara M.W. Carroll

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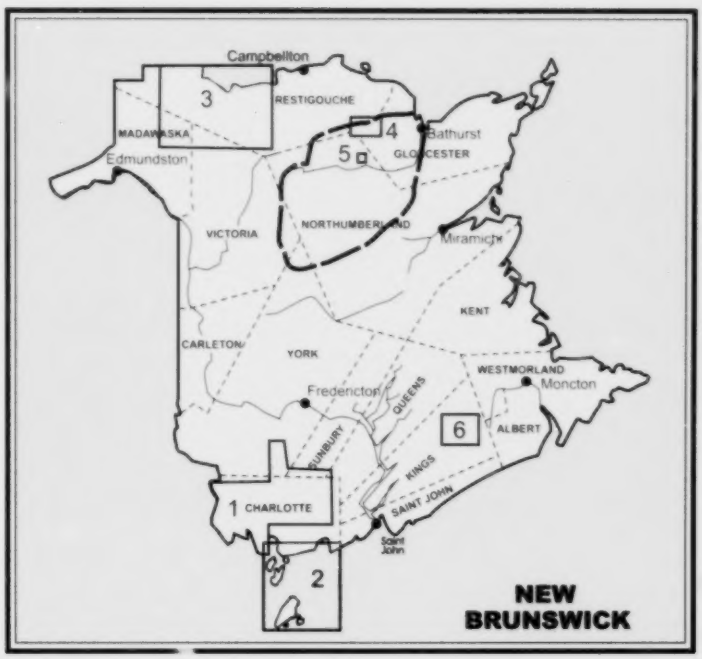

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Cover Illustration: Index to papers in this volume:

1. Glacial history, southwestern New Brunswick (Allard, Pronk)
2. New U–Pb ages, Grand Manan & The Wolves islands (Barr, Miller, Fyffe, White)
3. Geology of Kedgwick, Gounamitz River, States Brook & Menneval map areas (Carroll)
4. Structure in vicinity of Rocky Brook–Millstream Fault (Dimitrov, McCutcheon, Williams)
5. A'Hearn Brook Zn–Pb–Cu–Ag deposit (Walker, McCutcheon)
6. Stratigraphy, evaporite structure, tectonic history in McCully area (Wilson)

Bathurst Mining Camp

This report has been prepared by:

Minerals, Policy and Planning Division
Department of Natural Resources
Province of New Brunswick

Hon. Keith Ashfield
Minister of Natural Resources

November 2003

104-01937/

ERRATA

Page 14 – White area, in left-centre part of the map, containing abbreviation FB-TBF:
This area should show only the hatched pattern for the Silurian Devonian Saint George Batholith.

Page 31 – Overprinting of patterns, in lower right-hand corner:
The diagonal pattern (SDTBS) should not extend into DTC.

Page 51 – Paragraph 2, line 9, pertaining to the Sainte-Florence Fault:

> "Malo and Bourque (1993) interpret the fault as a northwestward directed (i.e. northwest dipping) Acadian thrust. If this is the case, the movement on the fault is relatively limited because the rocks on the hanging-wall (over-thrusted) side are younger than those on the foot-wall side."

should read:

> Malo and Bourque (1993) interpret the fault as a northwestward-directed (i.e. *southeast* dipping) Acadian thrust. If this is the case, the movement on the fault is relatively limited because the rocks on the hanging-wall side *(Temiscouata Formation) are not significantly older than those on the foot-wall side (York Lake Formation).*

Page 61 – The grid pattern of the Intrusive Rocks is missing (see attached replacement figure).

Page 75 – The patterns are overlapping (see attached replacement figure).

Page 77 – The colour of the Flat Landing Brook Formation (orange) should not extend into the hatched pattern of the Roger Brook Member.

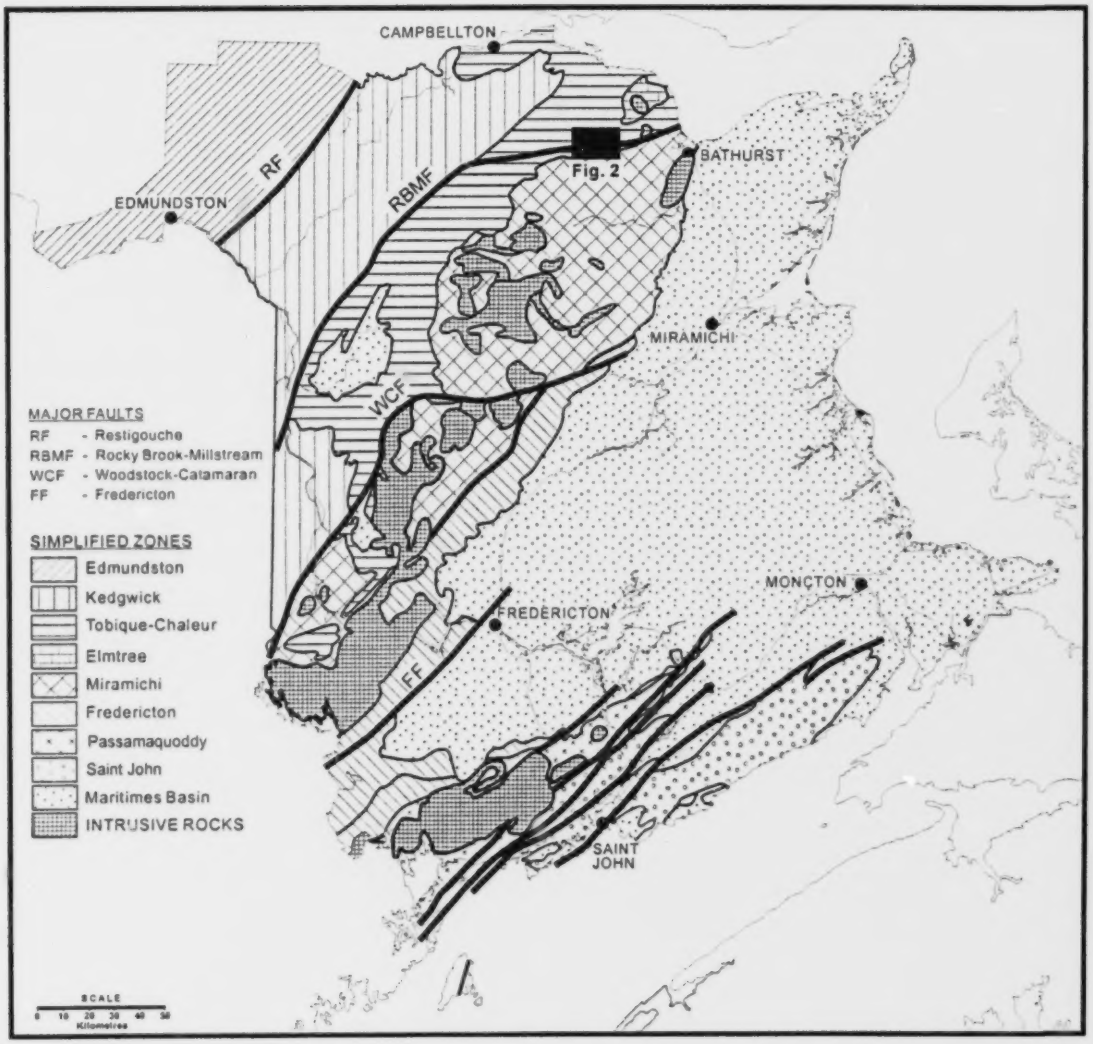

Figure 1. Simplified geological map showing the major faults and metallogenic zones in New Brunswick (modified after Fyffe 2002) and the location of Figure 2.

features that extend over a considerable distance and is accompanied by an array of distinctive physiographic features such as sag ponds, deflected river valleys or dry valleys. The second system of lineaments, which is parallel to a common fault direction, trends to the northwest and has a less pronounced effect on topography. Nonetheless, these lineaments are clearly recognizable and more closely spaced than the first group. The less pronounced topographic expression of the northwestern system may reflect the direction of glacial transport, which is from west to east. The negative landforms that are at a high angle to the direction of glacial flow tend to be filled with sediments. This study and another by Williams *et al.* (1995) show that northwest-trending faults are generally younger than the northeast-trending set.

STRATIGRAPHY

The Silurian Chaleurs Group has been subdivided into ten formations, in ascending stratigraphic order, namely: Clemville, Weir (formerly Armstrong Brook), Upsalquitch, La Vieille, Simpsons Field,

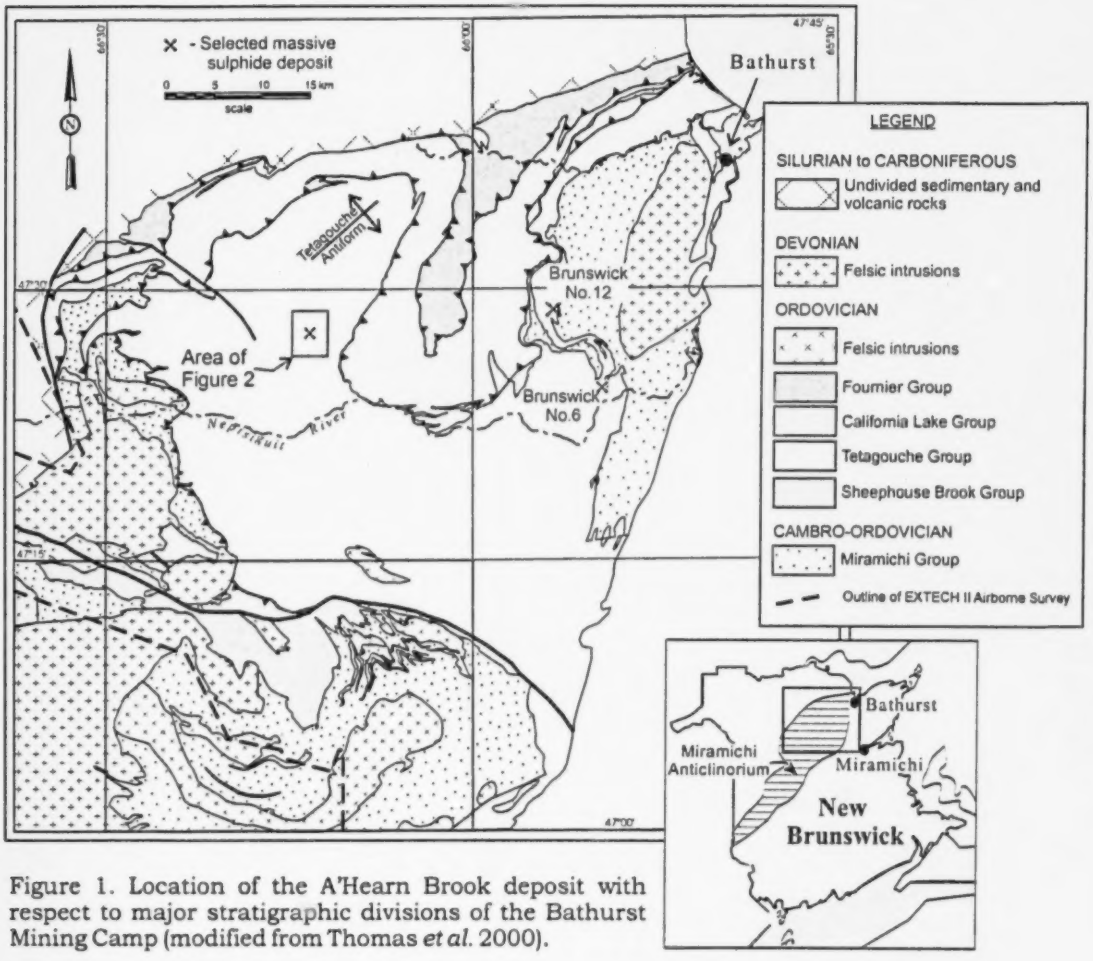

Figure 1. Location of the A'Hearn Brook deposit with respect to major stratigraphic divisions of the Bathurst Mining Camp (modified from Thomas *et al.* 2000).

sulphide lens was drilled to a depth of 544 m (Beaumont-Smith 1995), and was successful in intersecting two mineralized horizons, although the base-metal grades were very low.

Most recently Slam Exploration Ltd. carried out a trenching and shallow diamond-drilling program (drill holes OH-02-01 through OH-02–06) on the property (Brown 2002). The position of drill-hole collars and trench locations from which data were compiled are located on Figure 3.

REGIONAL GEOLOGY

The Bathurst Mining Camp comprises a polydeformed Middle Ordovician sequence of bimodal volcanic and intercalated sedimentary rocks deposited in a back-arc basin that formed on Cambro-Ordovician siliciclastic rocks (flysch sequence) bordering a stable peri-Gondwanan continental margin (van Staal and Fyffe 1991).

The Bathurst Mining Camp contained a pre-mining geologic resource of 349 000 000 t of massive sulphide (McCutcheon *et al.*, in press). Since the discovery of the Brunswick No. 6 ore body in 1952 (Belland 1992), the camp has produced more than 134 000 000 t of ore grading 3.05% Pb, 7.82% Zn, 0.46% Cu and 91.5 g/t Ag (McCutcheon *et al.*, in press). There are 46 known volcanogenic massive sulphide deposits in the Bathurst Mining Camp and all are spatially associated with felsic

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S.M. Barr[1], B.V. Miller[2], L.R. Fyffe[3], C.E. White[4]
[1] Department of Geology, Acadia University
[2] Department of Geological Sciences, University of North Carolina
[3] Geological Surveys Branch, New Brunswick Department of Natural Resources
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GLACIAL HISTORY OF SOUTHWESTERN NEW BRUNSWICK: CHALLENGES TO DRIFT PROSPECTING †

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ALLARD, S. and PRONK, A.G. 2003. Glacial history of southwestern New Brunswick: challenges to drift prospecting. *In* Current Research 2002. *Edited by* B.M.W. Carroll. New Brunswick Department of Natural Resources; Minerals, Policy and Planning Division, Mineral Resource Report 2003-4, pp. 1–11.

Seven hundred and thirty-two till samples have been collected from southwestern New Brunswick. These samples have been subjected to geochemical, lithological, and granulometric analyses in an attempt to delineate potential exploration targets and characterize the glacial history of the area. A single basal till unit of local derivation occurs in the study area. Texture and colour reflect local bedrock units. Major till deposition was accomplished by an Early–Middle Wisconsinan southeastward flowing ice sheet. This till unit was subsequently reworked (imprinted) by one, or more, relatively weak Late Wisconsinan ice-flow events. The younger events did not produce a recognizable deposit but, instead, altered the pre-existing till through a moderate redistribution of the matrix components, slight redistribution of the clast medium and realignment of clast fabric. The result is the formation of a hybrid till, with characteristics indicative of multiple ice flow events. The observations discussed here, and the lack of complex glacial/deglacial stratigraphy, indicate that the Late Wisconsinan ice-flow trajectories represent a shift in outflow orientation within a common ice sheet, rather than multiple advances and retreats by individual ice masses. Geochemical dispersal patterns tend to form short high-contrast bull's-eye- or amoeboid-shaped anomalies that extend approximately 5 km down-ice of the presumed source, although some anomalies are considerably longer (up to 30 km). These longer ribbon-shaped dispersal trains parallel landform fluting and clearly demonstrate the dominance of southeastward transport.

Sept cent trente-deux échantillons de till ont été prélevés dans le Sud-Ouest du Nouveau-Brunswick. On a soumis ces échantillons à des analyses géochimiques, lithologiques et granulométriques pour essayer de délimiter des objectifs d'exploration et de caractériser le passé glaciaire du secteur. Une seule unité de till de fond est présente dans le secteur d'étude. Sa texture et sa couleur correspondent aux unités de substrat rocheux. L'écoulement vers le sud-est d'une nappe glaciaire au cours du Wisconsinien précoce-moyen a entrainé une sédimentation importante de till. Cette unité de till a subséquemment été remaniée (marquée) par un ou plusieurs écoulements glaciaires relativement faibles du Wisconsinien tardif. Les écoulements plus récents n'ont pas produit de gîte reconnaissable, mais ont plutôt altéré le till préexistant par une redistribution moyenne des éléments de la matrice, une redistribution légère du support des clastes et un remaniement de la fabrique des clastes. Le processus a abouti à la formation d'un till hybride dont les caractéristiques témoignent de plusieurs écoulements glaciaires. Les observations signalées aux présentes et l'absence d'une stratigraphie glaciaire/déglaciaire complexe révèlent que les trajets des écoulements glaciaires du Wisconsinien tardif représentent un changement d'orientation de l'écoulement à l'intérieur d'une nappe glaciaire commune plutôt qu'une série de progressions et de reculs de masses glaciaires individuelles. Les modes de dispersion géochimique forment généralement des anomalies courtes à contraste élevé et de forme amiboïde ou concentrique qui s'étendent sur environ cinq kilomètres en aval de la source

† New Brunswick Geological Surveys Branch ordinary budget.

Figure 2. Generalized bedrock geology of southwestern New Brunswick showing the study area (Wilbur et al. 1997).

INTRODUCTION

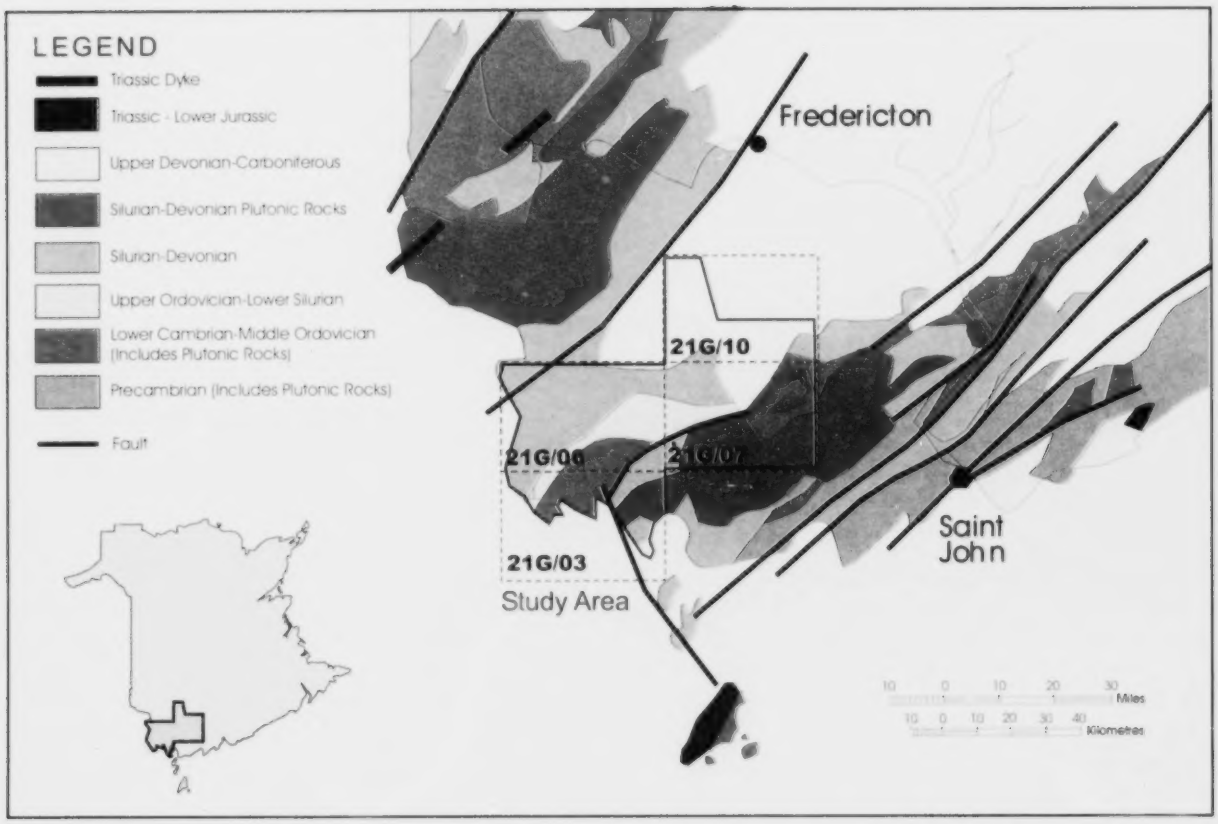

Figure 1. Generalized bedrock geology of southwestern New Brunswick showing the study area (Fyffe *et al.* 1997).

présumée, bien que certaines anomalies soient considérablement plus longues (jusqu'à 30 kilomètres). Ces tracés de dispersion rubanés plus longs et parallèles au rainurage de la topographie démontrent clairement la prédominance du transport vers le sud-est.

INTRODUCTION

In recent years, mineral exploration activity has substantially increased in southwestern New Brunswick, due in large part to the delineation of gold skarn deposits at the Clarence Stream property of Freewest Resources Canada Inc. In response to this, till sampling has been conducted in the McDougall Lake (NTS 21 G/07), Rollingdam (21 G/06), and St. Stephen (21 G/03) map areas and the southern third of Fredericton Junction (21 G/10) map area (Figure 1). Sample density was one sample per 4 km^2. Seven hundred and thirty-two samples were collected and subsequently subjected to geochemical (ICP-MS and INAA), lithological and granulometric analyses. Figure 1 shows the study area in relation to the bedrock geology of southwestern New Brunswick.

Detailed field data and geochemistry listings have been published (Pronk *et al.* 2002a and b). A detailed description of sampling procedures and analytical methodology is presented by Allard (2003). Although the primary focus of this study is to identify potential mineral exploration

targets, attention is also given to the delineation of glacial transport trajectories in this area of complex ice-flow history. A comprehensive understanding of glacial history is considered an important factor in the interpretation of till geochemistry data. The goal of this paper is to address this issue by providing a better understanding of the glacial dynamics that occurred in southwestern New Brunswick.

PREVIOUS WORK

Preliminary work describing the glacial history of southwestern New Brunswick began as early as the mid-1800s (Robb 1851; Hind 1865; Matthew 1872, 1879). By making note of glacial striae orientations throughout the course of their bedrock examinations, they developed the idea that glaciation comprised one mass of ice flowing in a south-southeasterly direction.

Chalmers (1890) expanded upon this concept by proposing that the province was glaciated by an "Appalachian system of glaciers" rather than by one vast ice cap. Furthermore, he postulated that striae indicating south-southeasterly flow, observed in southwestern New Brunswick, were the result of glaciation by local ice caps centered in the highlands of New Brunswick and New England (Chalmers 1890).

Lee (1957, 1962) was among the first to characterize and map surficial materials in southwestern New Brunswick, although Wicklund and Langmaid (1953) conducted an earlier regional soil survey that provided some information regarding glacigenic sediments and their relevance to the genesis and physical attributes of overlying soils. More recent works by Gadd (1973) and Rampton *et al.* (1984) describe the composition and extent of surficial materials while also providing a comprehensive interpretation of glacial history.

Rampton *et al.* (1984) revised Chalmers' hypothesis of an "Appalachian system of glaciers" by suggesting that four local ice centres affected New Brunswick during the Late Wisconsinan. Two of these, the North Maine–Notre Dame Ice Divide centred in the highlands of New England and Quebec (White Mountains, Megantic Hills, Gaspé Peninsula), and the proposed Gaspereau Ice Centre in the New Brunswick Lowlands, were thought to have impinged upon southwestern New Brunswick (Rampton *et al.* 1984). Follow-up studies by Seaman (1989a, 1989b, 1989c) and Seaman *et al.* (1993) characterized the extent and chronology of erosional ice-flow events through an extensive analysis of striated outcrops.

OBSERVATIONS AND RESULTS

Basal till characteristics

A single basal till unit of regional extent, comprising both basal melt-out and lodgement till, was encountered during fieldwork in the study area. A single exception will be discussed below. Typically only one member was present at each sample location; however, some exposures displayed a gradation from basal melt-out till into lodgement till. Despite this, no attempt was made to sample one medium exclusively. Both sub-groupings of basal till found throughout the study area are remarkably similar in terms of physical attributes. Distinguishing between the two with consistency in the field from one sample site to another is extremely difficult. Both are composed of the same fragmental rock material derived from the basal load of the ice mass and, therefore, belong to the same facies (subglacial melting-ice facies of Brodzikowski and Van Loon 1987). They are geochemically and lithologically identical and differ only in the mechanics involved in their deposition.

The basal till unit predominantly occurs as a blanket or veneer, covering large parts of the landscape. Sections of at least three metres in thickness were noted in some areas, predominantly on the lee side of topographic highs, while veneers only a few decimeters in thickness or less were often found to cover areas with abundant bedrock exposures at the surface. Commonly, the thickness of the basal till ranges from 1 m to 1.5 m. In close proximity to the coast, till deposits tend to be more sporadic and thin.

Collected samples are matrix-supported and have a characteristic bimodal particle size distribution. Clasts range from pebble-size to cobble-size and are typically sub-angular to angular and of local derivation: lithological analysis revealed only a small percentage of erratics. Average matrix granulometry is in the range of 50% sand, 35% silt, and 15% clay. See Allard (2003) for a detailed description of methodology used to determine grain size distributions.

Till samples ranged from very friable to very compact. This large discrepancy in compaction can be attributed to genetic factors and, to a lesser extent, moisture content and the relative amount of fines (clay and fine silt) within the till. Basal till colour is quite consistent across the study area, closely reflecting the colour of underlying bedrock units.

As alluded to above, one sample site demonstrated a unique stratigraphic - profile in contrast to that normally encountered in the study area. Along Peltoma Lake Road in the Fredericton Junction area a multiple till section was discovered. This site is characteristic of two inherently different basal tills separated by approximately two metres of ice contact sediment. Although it is likely that this stratigraphy simply represents a decollement between the ice and substrate during glacial advance, it is possible that the upper till (extent unknown) represents a distinct basal till unit deposited during a late glacial advance (Younger Dryas?).

Currently, Michel Lamothe (University of Quebec at Montreal) is conducting preliminary tests to assess whether it is feasible to use the thermoluminescence dating technique to date the ice contact sediment. If the upper till is deemed a Younger Dryas till, it is only a localized phenomenon. Proximal to this multiple till section is Splan Pond, a small water body situated on drift-veneered bedrock near Moores Mill, which has recorded evidence of the Younger Dryas in its sediments. Although the record shows evidence of a cooling phase, pollen profiles show that the lake was ice-free during this time (Levesque *et al.* 1996).

Erosional indicators

In conjunction with the till sampling program, attention was given to the examination of ice-flow indicators. Accurate measurement of striae and other micro-fluting features was conducted and, where possible, chronological relationships were established. Although a multitude of orientations were recorded, some regional trends were noted. In the western part of the study area, the dominant striae orientation is toward the southeast (~140°) while the eastern portion (Fredericton Junction and McDougall Lake map areas) is dominated by southerly and south-southwesterly oriented striae.

The terrain surface of most of the study area is undulating due to the widespread occurrence of streamlined ridges aligned in a northwest–southeast direction. These ridges are the result of extensive glacial fluting and drumlinization and can clearly be seen on aerial photographs or topographic maps of the study area (Figure 2). Orientation of these ridges and drumlins ranges from approximately 130°–145° and reflects the dominant erosional ice-flow orientation traversing the study area. Rampton *et al.* (1984) attribute similar southeasterly trending striae and landforms

Figure 2. Oblique aerial photograph of the Canoose Flowage in the Rollingdam map area. The observed glacial fluting is characteristic of much of the study area. Photograph courtesy of Martin Marshall (Protected Natural Areas).

found in southeastern New Brunswick to ice activity during the Early–Middle Wisconsinan and term this the Caledonia flow pattern or Caledonia phase of glaciation (>53 ka B.P.). Seaman *et al.* (1993) expand on this and suggest that the correlative southeasterly trending striae and glacial landforms characteristic of southwestern New Brunswick are also the result of the Caledonia phase glaciation.

Till fabric analysis

Till fabric analysis was conducted at various localities within the study area with particular focus on the Rollingdam map area (NTS 21 G/06). Sections of lodgement till were selected for analysis only if the following criteria were met: (1) acceptable vertical profile (road cut or excavation); (2) matrix-supported fabric; (3) high degree of compactness; and (4) practical availability of elongated clasts. Only clasts exhibiting a minimum 1.5:1 length-to-width ratio were used and these clasts were characterized spatially by noting their orientation and dip, and then measured along their length (a-axis) and width (b-axis).

Most till fabrics in the Rollingdam map area show strong clast alignment toward the south-southwest (~200°–220°) with only slight variation, while others shows strong alignment toward the southeast (~140°) as well as moderate alignment toward the south (~180°) and south-southwest (~205°). The Rollingdam area was of particular interest due to the fact that most till fabrics were found to be aligned toward the south-southwest, even in areas of intense drumlinization toward the southeast. The factors leading to this unusual relationship are discussed below.

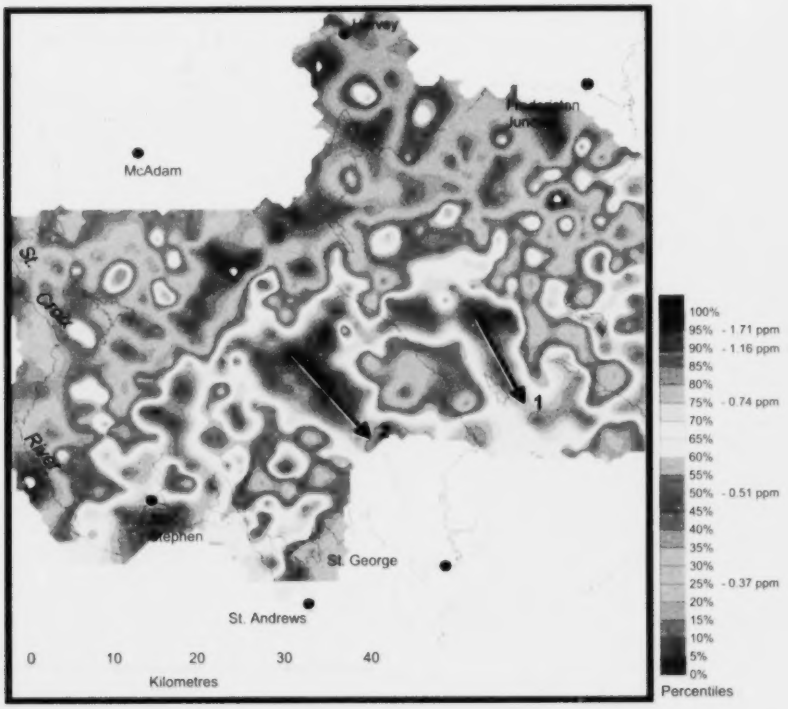

Figure 3. Molybdenum (Mo) concentration in till. Method of analysis is ICP-MS.

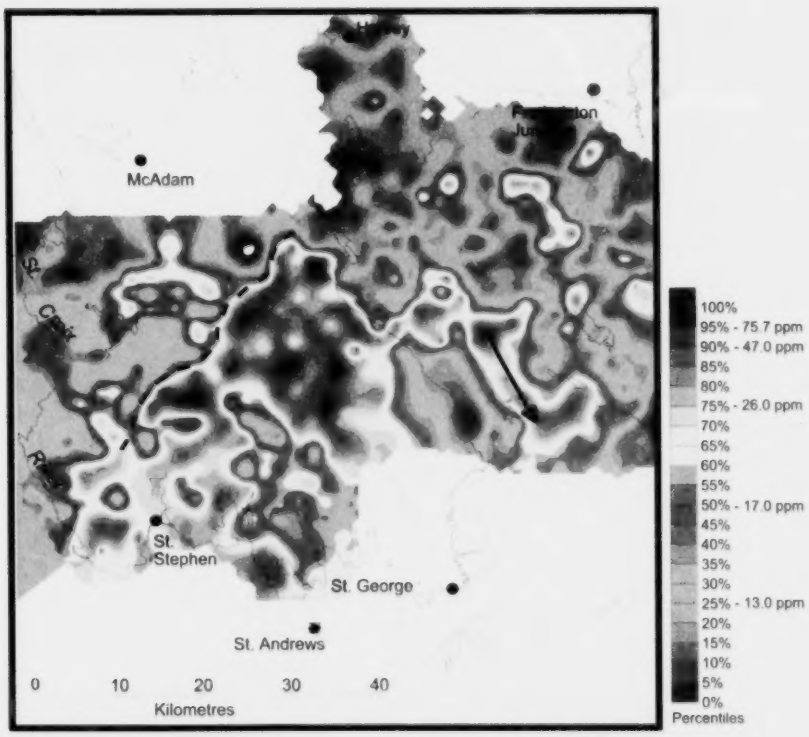

Figure 4. Arsenic (As) concentration in till. Method of analysis is INAA.

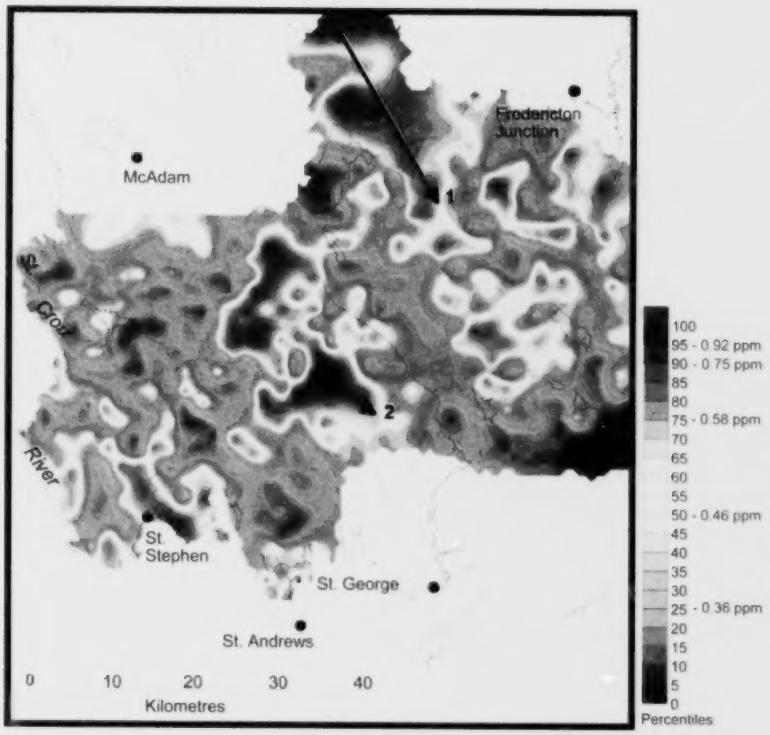

Figure 5. Antimony (Sb) concentration in till. Method of analysis is ICP-MS.

Till geochemistry analysis

The results obtained from geochemical analysis of the collected till samples were used to assess the direction and extent of glacial dispersal in the study area. Selected matrix geochemistry contour plots that best demonstrate these trends are discussed here. The Surfer® 8 program was used to contour the raw data using point kriging as the method of contouring (Allard 2003).

In most cases, geochemical anomalies occur as high-contrast bull's eye- or amoeboid-shaped dispersal patterns with an exponential decrease in concentration just down ice of the presumed source. A few elements show considerably longer trains, up to 25–30 km in some cases. It should be noted that among some elements geochemical dispersal is possibly complicated by a small degree of epigenetic redistribution (groundwater remobilization or the occurrence of slope processes). However, these redistributions are of minimal consequence in southwestern New Brunswick (Allard 2003) and, for the most part, any observed high-contrast dispersal patterns are the direct result of actively advancing ice (syngenetic).

Elemental contour diagrams presented here include molybdenum (Figure 3), arsenic (Figure 4) and antimony (Figure 5). Evident in the molybdenum plot are two well-defined dispersal trains emanating from the Mount Pleasant and Clarence Stream areas. These are denoted by arrows 1 and 2, respectively (Figure 3). The Mount Pleasant dispersal train appears as an approximately 25 km long ribbon-shaped anomaly oriented toward the southeast (~150°). Dispersal train #2 (as labelled in Figure 3) spans a distance of approximately 20 km and is also oriented toward the southeast (~140°).

Figure 3 - Molybdenum (Mo) concentration in till - Method of analysis is ICP-MS.

Figure 4 - Arsenic (As) concentration in till - Method of analysis is INAA.

Figure 3 Arithmetic Sb concentration in till. Method of analysis is ICP-MS.

Till geochemistry analysis

The results obtained from geochemical analysis of the collected till samples were used to assess the direction and extent of glacial dispersal in the study area. Selected matrix geochemistry contour plots that best demonstrate these trends are discussed here. The Surfer® 8 program was used to contour the raw data using point kriging as the method of contouring (Allard 2003).

The most subtle geochemical anomalies occur as high-contrast 'bull's eyes' or unstructured-shaped dispersal patterns with an exponential decrease in concentration laid down level of the presumed source. Many elements show considerably longer trains, up to 25–30 km in some cases. It should be noted that among some elements geochemical dispersal is possibly complicated by a small degree of epigenetic redistribution (groundwater) superimposed on the syngenetic glacial processes. However, these redistributions are of minimal consequence in southwestern New Brunswick (Allard 2003) and, for the most part, the observed anomalous dispersal patterns are the direct result of glacier-advanced ice movement.

Elemental contour diagrams presented here include manganese oxide (Figure 4) and aluminum (Figure 5). Evident in the manganese and aluminum dispersal trains are two distinct trends emanating from the Mount Pleasant and Harvey Settlement areas. These are denoted by arrows 1 and 2 respectively (Figure 3). The Mount Pleasant dispersal train appears as an approximately 25 km long ribbon shaped anomaly oriented toward the southeast (~150°). Dispersal train 2, as labelled in Figure 3, exists at distances of approximately 20 km and is also oriented toward the southeast (~140°).

Arsenic and molybdenum show similar anomalous patterns. Again, an approximately 25 km long ribbon-shaped anomaly can clearly be seen extending from the Mount Pleasant area as denoted by the arrow in Figure 4. Also of interest in the arsenic contour plot is the sharp contrast in geochemical relief approximated by the hatched line traversing the diagram (Figure 4). This line roughly coincides with a major bedrock boundary that separates the Silurian rocks to the north from the Upper Ordovician–Lower Silurian rocks to the south (Figure 2). This shows the extent of control that the underlying bedrock exerts on till geochemistry in southwestern New Brunswick and attests to the relatively local nature of the basal till.

Interesting dispersal features are also apparent in the antimony contour diagram (Figure 5). An approximately 30 km long dispersal train, truncated by the upper boundary of the study area, extends southeast (~145°) from the Harvey area (Figure 5). This anomaly can be attributed to two potential sources. One is the Harvey Mountain Formation volcanic rocks and the other is the Lake George antimony mine area (Seaman 2000). If this dispersal feature originated from the Lake George area, it indicates a transport distance of approximately 40 km (Seaman 2000).

INTERPRETATIONS

The presence of multiple syngenetic dispersal trains oriented toward the southeast (~140°–150°) and the fact that a single basal till unit was encountered indicates that only one major depositional ice-flow event affected the study area during the Wisconsinan episode of glaciation. The southeasterly trend is apparent in the striae record and is consistent with the overall trend of erosive glacial landforms in the study area, hence indicating that the ice-flow event responsible for creating the observed dispersal patterns was characteristic of alternating phases of erosion and deposition. Seaman *et al.* (1993) attribute this flow pattern to ice activity during the Early Wisconsinan (>53 ka B.P.) and relate this to the Caledonia phase of Rampton *et al.* (1984).

Although a multitude of striae orientations were documented in the study area, many of which correlate to Late Wisconsinan flow paths delineated by Seaman *et al.* (1993), none seem to have had a profound effect on the study area. As mentioned above, only one stratigraphic basal till unit was encountered in the field (with one exception, discussed earlier) and it can be said with near certainty that this till was deposited during the Caledonia phase. However, by examining palimpsest landforms (Parent *et al.* 1996), geochemical dispersal patterns and till fabrics in the Rollingdam area, Allard (2003) has delineated a south-southwesterly Late Wisconsinan flow pattern that has had some effect on the Early–Middle Wisconsionan till. Integral to this deduction is the fact that till fabric is aligned toward the south-southwest in areas characterized by a strong southeasterly landform alignment (fluting and drumlinization). The implication of this is that southeasterly erosion and dispersal must have pre-dated south-southwesterly dispersal. A south-southwesterly trending till fabric would not have been preserved if the converse were true, as it would have been destroyed by the highly erosive southeasterly trending ice-flow phase. Maximum south-southwest (~200°–220°) geochemical dispersal in the Rollingdam area is on the order of 3–5 km (Allard 2003).

In this scenario, the late south-southwesterly ice flow event (200°–220°) did not produce a recognizable deposit but instead it left its mark by altering the pre-existing till (e.g., Broster and Dreimanis 1981). This alteration takes the form of a modest redistribution of the till matrix and, to a lesser extent, the clast component, as well as a re-alignment of the till fabric toward the south-southwest. Stea and Finck (2001) refer to the process of imprinting matrix, clast or fabric components on older tills as inheritance, and Grant (1963) defines a hybrid till as a till whose properties were defined by the re-working of pre-deposited till by the action of overriding ice. By adhering to this nomenclature it can be stated that hybrid till blankets much of the study area.

Continued study may lead to the delineation of additional Late Wisconsinan flow events that have imprinted and slightly reworked the single basal till unit of regional extent. However, the lack of complex glacial/deglacial stratigraphy indicates that these various Late Wisconsinan flow trajectories would simply represent a shift in outflow orientation within a common ice sheet, rather than multiple glacial advances and retreats by individual ice masses.

CONCLUSIONS

Southwestern New Brunswick has a complex Wisconsinan glacial history and, therefore, presents unique challenges to drift exploration. The conclusions derived from this study, listed below, reflect the broad scope of this project. They are meant to provide insight into the glacial processes at work and their implications to any future drift prospecting/exploration in the area.

1. One stratigraphic basal till unit, consisting of both basal melt-out till and lodgement till, was encountered in the study area. This unit was deposited during the Caledonia phase of glaciation (Early–Middle Wisconsinan) followed by minor reworking (imprinting) during Late Wisconsinan ice-flow events. The later events did not produce a recognizable deposit but rather, they altered the physical properties of the pre-existing till. The result is a hybrid till. Detailed study in the Rollingdam map area (NTS 21G/06) has led to the delineation of one such Late Wisconsinan ice-flow event. It followed a south-southwest (200°–220°) flow trajectory.

2. Basal till throughout the study area comprises predominantly locally derived fragmental rock material with colour and texture reflective of the local bedrock units. Till geochemistry is closely associated with the underlying bedrock geology and, therefore, the basal till is deemed an effective exploration medium.

3. Transport distances in the geochemical medium are in the order of 20–25 km and follow a southeasterly trajectory from known sources.

4. The observations discussed here, and the lack of complex glacial/deglacial stratigraphy, indicate that the various Late Wisconsinan flow trajectories represent a shift in outflow orientation within a common ice sheet, rather than multiple advances and retreats by individual ice masses.

5. Till sampling at a density of one sample per 4 km^2 and analysis of the silt plus clay (<0.063 mm) fraction of the sample is efficient in identifying regional scale geochemical trends.

ACKNOWLEDGEMENTS

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NEW U–PB AGES FROM GRAND MANAN AND THE WOLVES ISLANDS, SOUTHERN NEW BRUNSWICK †

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BARR, S.M., MILLER, B.V., FYFFE, L.R., and WHITE, C.E. 2003. New U–Pb ages from Grand Manan and The Wolves islands, southern New Brunswick. *In* Current Research 2002. *Edited by* B.M.W. Carroll. New Brunswick Department of Natural Resources; Minerals, Policy and Planning Division, Mineral Resource Report 2003-4, pp. 13–22.

Felsic metatuff from Ingalls Head on Grand Manan Island in the Bay of Fundy yielded a U–Pb zircon age of 618±3 Ma. Granite underlying Three Islands, located about 8 km south of Ingalls Head, yielded a similar age of 611±3 Ma. These Neoproterozoic ages suggest a link with the Avalon terrane of the northern Appalachian orogen.

Quartz monzodiorite from The Wolves Islands, located in the Bay of Fundy about 12 km south of the New Brunswick mainland, yielded an age of 437±5 Ma. This Early Silurian age is similar to ages reported from volcanic and granitic rocks in the Kingston terrane of mainland southern New Brunswick. Although The Wolves Islands have previously been considered as part of the Late Neoproterozoic–Early Cambrian Brookville terrane based on the extension of onshore trends, no igneous units of Silurian age are known in either the Brookville or adjacent Caledonian terranes, so correlation with either of those areas is unlikely.

La datation au U–Pb à partir de zircon de métatuf felsique d'Ingalls Head sur l'île Grand Manan, dans la baie de Fundy, a situé son âge à 618±3 Ma. La datation de granite sous-jacent à Three Islands, à environ huit kilomètres au sud d'Ingalls Head, a attribué à celuici un âge similaire de 611±3 Ma. Ces âges remontant au Néo-Protérozoïque laissent supposer un lien avec le terrane d'Avalon de la partie nord de l'orogène des Appalaches.

La datation de monzodiorite quartzeuse des îles The Wolves, situées dans la baie de Fundy à une douzaine de kilomètres de la partie continentale du Nouveau-Brunswick, lui a conféré un âge de 437±5 Ma. Cet âge la situant au Silurien inférieur est similaire aux âges obtenus de roches volcaniques et granitiques du terrane de Kingston dans le sud intérieur du Nouveau-Brunswick. Même si les îles The Wolves ont déjà été considérées comme une partie du terrane du Néoprotérozoïque–Cambrien inférieur de Brookville en vertu du prolongement des directions des couches côtières, on n'a encore relevé aucune unité ignée du Silurien dans le terrane de Brookville ni dans le terrane calédonien adjacent, de sorte qu'il est peu probable qu'il existe une corrélation avec l'un ou l'autre de ces secteurs.

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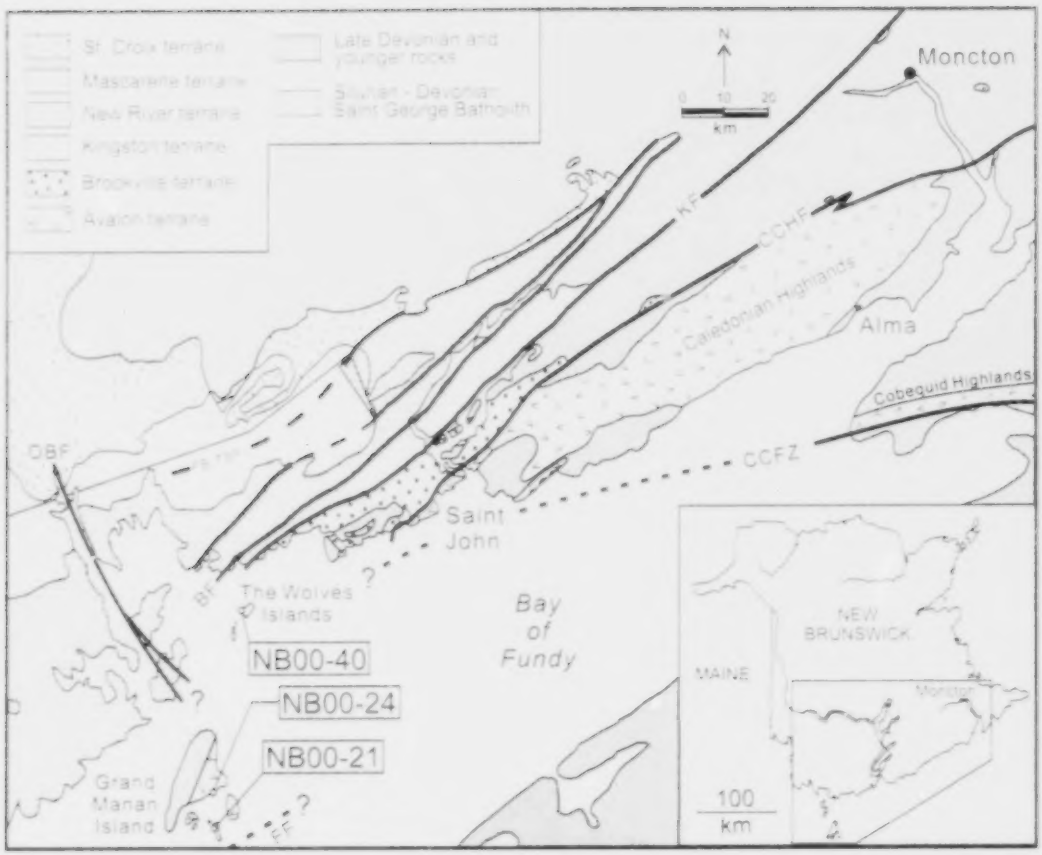
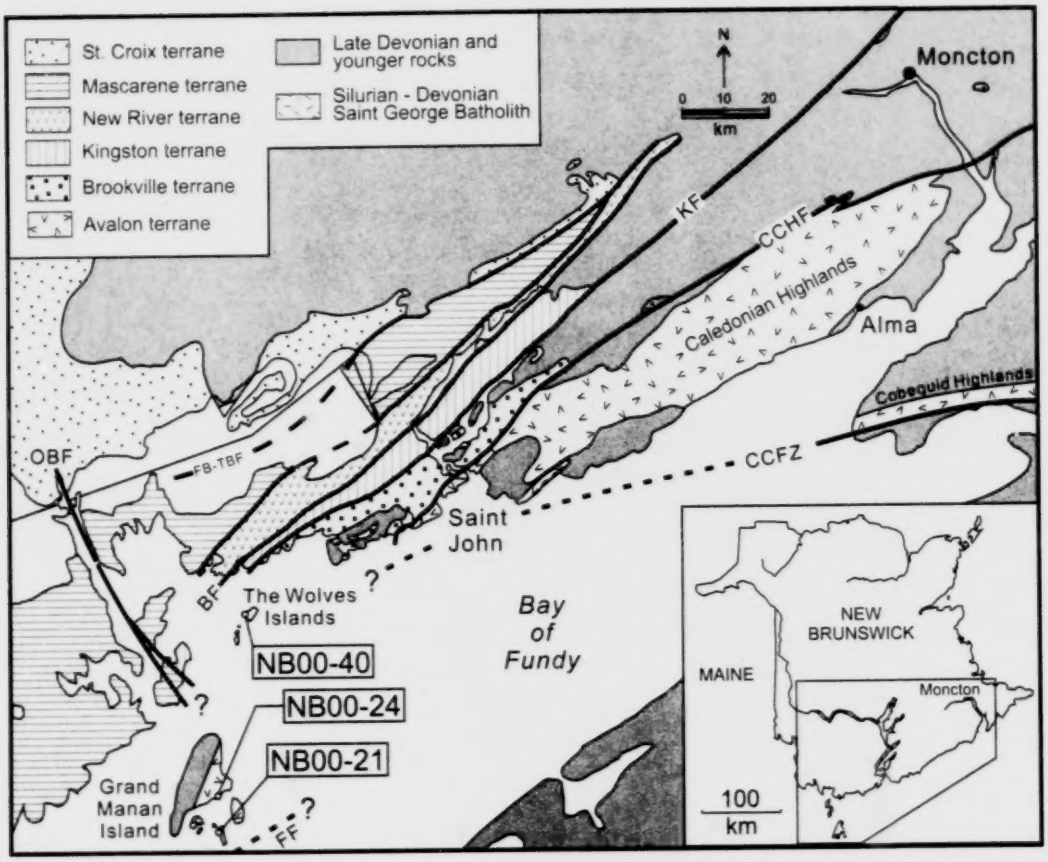


Figure 1. Terranes in southern New Brunswick, showing the location of Grand Manan Island and The Wolves Islands (after Barr *et al.* 2002). Abbreviations: BF – Belleisle Fault; CCFZ – Cobequid-Chedabucto Fault zone; CCHF – Caledonia–Clover Hill Fault; FF – Fundy Fault; KF – Kennebecasis Fault; OBF – Oak Bay Fault.

INTRODUCTION

During the past 15 years, precise U–Pb dating of zircon has provided new insights into the ages of igneous rocks in southern New Brunswick. Many of the ages differ from previously assumed ages, in some cases older and in other cases younger and, hence, they have contributed significantly to our current understanding of this complex area. The purpose of this paper is to add to this growing database by presenting three new U–Pb zircon ages, two from Grand Manan Island and one from The Wolves Islands (Figure 1). These islands in the Bay of Fundy are strategically located for tracing geological terranes from southern New Brunswick offshore to the southwest (Figure 1). Radiometric ages for these previously undated rock units should contribute significantly to the correlation of geologic terranes between New Brunswick, Nova Scotia, and the State of Maine.

Dating was done by Miller at the Isotope Geochemistry Laboratory at the University of North Carolina at Chapel Hill. Zircon grains were separated from ca. 25 kg samples, using standard techniques, sorted according to morphology and clarity under a binocular microscope, and abraded to remove the outermost portions of grains that are most likely to have been affected by Pb loss. Procedures and analytical techniques generally followed those described by Ratajeski *et al.* (2001). The complete data table for the new ages will be published elsewhere.



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GEOLOGICAL SETTING

Mainland southern New Brunswick is characterized by long narrow belts of rocks of contrasting composition and age, separated by major faults (Figure 1). The geological components of these belts or terranes have been described in various papers cited below and, hence, only summaries are presented here:

1. The Caledonia terrane consists of volcanic and sedimentary rocks of the ca. 620 Ma Broad River Group and Hammondvale metamorphic suite, and the ca. 560–550 Ma Coldbrook Group (Barr and White 1996; 1999; White *et al.* 2001). Widespread gabbroic, dioritic, granodioritic, and granitic plutons are cogenetic with the Broad River Group, and bimodal gabbroic and granitic plutons are cogenetic with basalt and rhyolite in the upper part of the Coldbrook Group. On the basis of petrological characteristics, the ca. 620 Ma rocks have been interpreted to have formed in a continental margin magmatic arc, whereas the ca. 560–550 Ma rocks formed in a subsequent extensional regime (Barr and White 1999). The Coldbrook Group is overlain by a Lower Paleozoic platformal sedimentary sequence containing an Avalonian fauna and traditionally termed the Saint John Group (e.g., Tanoli and Pickerill 1988; Landing 1996). Small areas of Ordovician volcanic rocks and Devonian volcanic and sedimentary rocks are also present. The Caledonia terrane is a typical part of the widespread Avalon terrane of the northern Appalachian orogen (e.g., Williams 1978).

2. The Brookville terrane is located northwest of the Caledonia terrane, from which it is separated by the Caledonia–Clover Hill Fault. It consists mainly of Proterozoic to early Cambrian rocks of the Green Head Group, Brookville Gneiss, Dipper Harbour Formation, and abundant plutons (White 1996; White and Barr 1996; White *et al.* 2002). The plutons range in composition from gabbroic through granitic, and have yielded U–Pb dates of ca. 555 Ma to 525 Ma (Bevier *et. al.* 1990; Dallmeyer *et al.* 1990; Currie and Hunt 1991; White 1996; White *et al.* 2002; Currie and McNicoll 1999). Petrological characteristics suggest that they constitute a typical calc-alkalic I-type granitoid suite, probably emplaced in a continental margin subduction zone (White 1996; White *et al. 2002*; Eby and Currie 1996). Although formed in a similar tectonic setting, they are more than 75 000 000 years younger than, and unrelated to, the ca. 620 Ma I-type gabbroic through granitic plutons of the Caledonia terrane. The Brookville terrane has been interpreted to be "basement" to the New River and St. Croix terranes (van Staal *et al.* 1996), but based on contrasts in Neoproterozoic and Cambrian histories, Barr *et al.* (2002) interpreted it to be a continental fragment separate from both Caledonia and New River terranes.

3. The Kingston terrane is separated from the Brookville terrane to the southeast by the Kennebecasis Fault, and from the New River terrane to the northwest by the Belleisle Fault (Figure 1). The Kingston terrane consists of Silurian metavolcanic and minor metasedimentary rocks of the Kingston Group, intruded by high-level comagmatic granitoid plutons and abundant mafic sheets (Barr *et al.* 2002). The mafic sheets and their host rocks were regionally metamorphosed to upper greenschist facies in the Late Silurian–Early Devonian, based on $^{40}Ar/^{39}Ar$ dates (Nance and Dallmeyer 1993). The volcanic and plutonic rocks of the Kingston terrane appear to be calc-alkalic, emplaced late in the evolution of a continental margin volcanic arc (Barr *et al.* 2002). In contrast, the mafic sheets are tholeiitic, and may have formed in a subsequent extensional tectonic regime. The relationship of the Kingston arc to Neoproterozoic rocks of terranes to the southeast (Brookville and Caledonia) and northwest (New River) is uncertain, but it may have formed on a continental fragment now represented by the New River terrane (Barr *et al.* 2002).

   A fault-bounded belt of mylonitic high-grade metamorphic rocks (Pocologan metamorphic suite) separates rocks of the Kingston terrane from mylonitic granitoid rocks of the Brookville terrane. The Pocologan metamorphic suite may represent an accretionary complex on the margin of the Kingston terrane (Barr *et al.* 2002).

4. The New River terrane, located northwest of the Kingston terrane, consists mainly of Neoproterozoic volcanic and plutonic rocks, in faulted contact with varied Cambrian volcanic and sedimentary units (Johnson and McLeod 1996; Johnson 2001). Ages of ca. 555 Ma and younger have been obtained from both volcanic and plutonic units in the New River terrane, but ca. 625 Ma ages have been obtained only from granitic units (Currie and McNicoll 1999; Currie and Hunt 1991). Part of the New River terrane appears to have linkages with the Ellsworth terrane in Maine and, hence, with Ganderia (Fyffe *et al.* 1999), but other parts have been suggested to be related to the Caledonia terrane (Johnson 2001).

5. The Mascarene terrane consists mainly of Silurian to Early Devonian siliciclastic sedimentary and volcanic rocks of the Mascarene Group, with widespread plutons of the Silurian–Devonian Saint George Batholith (Figure 1). Rocks of the Mascarene Group occur in several fault-bounded blocks each with distinct stratigraphy, but similar faunal assemblages suggest that they were part of a composite marine basin (Fyffe *et al.* 1999). Although contacts with rocks of the New River terrane are faulted, Fyffe *et al.* (1999) interpreted the Mascarene basin to have developed on the New River terrane, perhaps as a "back-arc" behind the Silurian Kingston arc. The northwestern margin is in faulted contact with Early Paleozoic rocks of the St. Croix terrane.

6. The St. Croix terrane is underlain by Late Cambrian (?) to Ordovican sedimentary and minor volcanic rocks of the Cookson Group. These early Paleozoic rocks are overlain with apparent conformity by Silurian sedimentary rocks of the Fredericton Trough. Recent interpretations have suggested that the St. Croix terrane has links to the Miramichi terrane of northern New Brunswick, and that both are part of the traditional Gander zone of the Appalachian orogen (van Staal and Fyffe 1995; van Staal *et al.* 1996, 1998).

The continuation of these terranes, especially Brookville and Caledonia, offshore into the Bay of Fundy to the southwest and onshore into the State of Maine is uncertain (e.g., Stewart *et al.* 2001), in part because geological relationships in much of the latter area are obscured by Silurian and Devonian volcanic and plutonic rocks of the Coastal Maine magmatic province (Hogan and Sinha 1989). McLeod *et al.* (2001) showed that Silurian rocks of the Kingston terrane extend to Campobello Island, where they plunge under the younger Quoddy Formation with relatively minor complexity related to offsets along the Oak Bay and related faults. If this interpretation is correct, then the simplest explanation is that The Wolves Islands should consist of rocks related to the Brookville terrane, and Grand Manan Island should include rocks related to the Caledonia terrane (Figure 1). However, the geological situation is complicated by thrust faults along the northern margin of the Fundy Basin (e.g., Nance 1987). These faults have been interpreted to be offset northeast of Grand Manan Island to connect with the Fundy Fault in the Gulf of Maine (Keen *et al.* 1991). Hence a straight-forward extension of the Brookville and/or Caledonia terranes to Grand Manan Island is unlikely, and onshore correlations of rock units in Grand Manan remain obscure.

GRAND MANAN ISLAND

Grand Manan Island consists mainly of Mesozoic rocks, including North Mountain basalt and underlying sedimentary rocks of the Blomidon Formation (e.g., Fyffe and Grant 2000, 2001). However, about one third of the island and small offshore islands are underlain by older, varied, and structurally complex metamorphic and igneous rocks (Stringer and Pajari 1981; Fyffe and Grant 2000, 2001). Early interpretations of the pre-Mesozoic rocks suggested correlation with Precambrian rocks of the Saint John area (Brookville and/or Caledonia terranes of Figure 1) (Alcock 1948; Potter *et al.* 1979). However, a Cambro-Ordovician age has been suggested for quartzose sandstone beds on Grand Manan Island due to their lithological similarity to the graptolite-bearing Cookson Group in the St. Stephen area of southwestern New Brunswick (Stringer and Pajari 1981). A few specimens of the trace fossil *Planolites* (Ron Pickerill, personal communication) occur on bedding surfaces in Flagg Cove, but this trace fossil has a wide age range.

McLeod *et al.* (1994) suggested similarity of rocks on Grand Manan Island to rocks in the Caledonia terrane of mainland New Brunswick, and divided the rocks into Precambrian–Cambrian (Ross Island Volcanics), Cambrian–Ordovician (Flag Cove and Priest Cove beds), and Silurian (North Head Volcanics) units. Microscopic fossil debris including inarticulate echinoderms, brachiopods, mollusks, and possibly bryozoans have been reported in volcaniclastic sandstone of the Priest Cove Beds (Hilyard 1992). Pe-Piper and Wolde (2000) have recently described the geochemistry of some of the volcanic rocks.

Fyffe and Grant (2000, 2001) published a revised interpretation of pre-Mesozoic geology on Grand Manan Island. They identified several new units, including the Ingalls Head Formation, a tuffaceous volcanic unit tentatively assigned to the Cambrian Ellsworth Group of Maine. They assigned various other units to the Green Head, Coldbrook, Cookson, and Mascarene groups of mainland New Brunswick. Granitic rocks on islands south of Grand Manan Island itself were named the Three Islands Granite, for which an Early Devonian age was suggested. The rock units are variably deformed and generally in faulted contact, and as a result stratigraphic relationships are difficult to determine (Fyffe and Grant 2001). As a follow-up to the mapping, samples were selected for U–Pb dating in an attempt to resolve the ages of units, and assist in making correlations with units on the mainland.

Sample NB00-24 was collected from the Ingalls Head Formation approximately 300 m north of Ox Head. The dated sample is a metamorphosed and deformed felsic tuff, and consists of scattered deformed plagioclase and alkali feldspar crystals and quartz aggregates in a fine-grained quartzofeldspathic matrix with relict flow-banding. Sericite is abundant. Zircon grains separated from sample NB00-24 were all very small prismatic (~50–75 μm x 20–40 μm) and spheroidal (~20–40 μm diameter) grains. The small size of these grains and the moderately low Pb concentrations necessitated multi-grain analyses. Despite the analysis of 9 to 40 grains per fraction, all seven zircon batches fall on a well-defined discordia line with an upper intercept of 618±3 Ma and a lower intercept suggestive of recent Pb loss (Figure 2a). We consider that the upper-intercept age is the time of zircon crystallization in the magma, and within error of the time of eruption of the tuff.

Sample NB00-21 was collected from the Three Islands Granite on Kent Island. It consists mainly of coarse K-feldspar and quartz in graphic intergrowth, with less abundant plagioclase. Minor (less than 2%) mafic minerals have been completely replaced by chlorite. Mainly prismatic zircon grains were separated from sample NB00-21. The tips of many grains were broken off during sample processing and three of the seven analyzed fractions consisted of these single grain tips. Four additional fractions include a whole, single prismatic grain and multi-grain fractions of prismatic grains of various sizes. Three analyses contain very low Pb concentrations and total common Pb was relatively high, leading to larger error ellipses. Nevertheless, all seven analyses form a discordant array with an upper intercept of 611.1±2.4 Ma, which we interpret as the time of zircon crystallization and, within error, the time of granite emplacement (Figure 2b).

THE WOLVES ISLANDS

Ritchie (1985) showed that East Wolf Island, the largest of The Wolves Islands (Figure 1), is underlain mainly by granitic rocks, intruded by scattered mafic dykes. This work was corroborated during the present study by a reconnaissance examination of outcrops around the shore of East Wolf Island, and also adjacent smaller islands. However, the rocks appear more heterogeneous than suggested by Ritchie (1985), and include, for example, quartz diorite and minor coarse-grained granite, in addition to the dominant biotite–hornblende quartz monzodiorite to tonalite. Based on their appearance, Barr *et al.* (2001) concluded that the granitoid rocks are probably related to those of the Brookville terrane on the mainland.

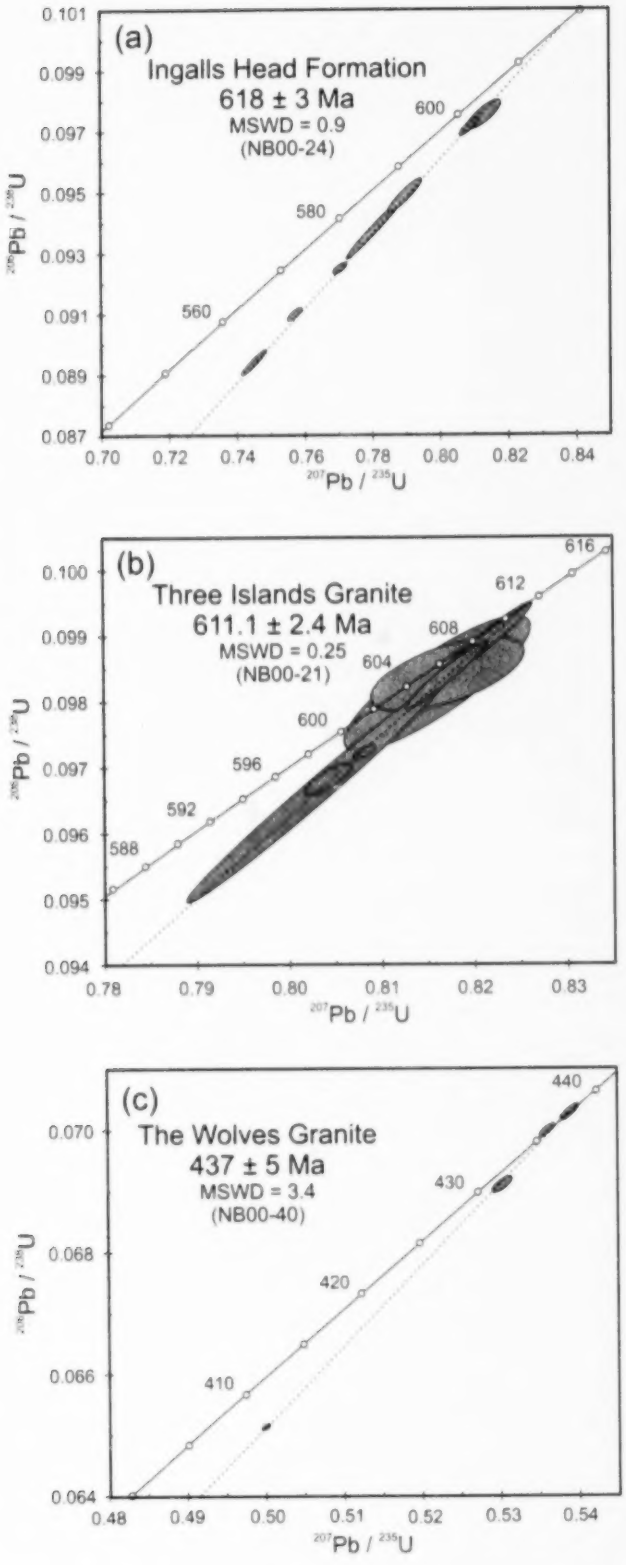

Figure 2. U–Pb concordia diagrams for (a) Ingalls Head Formation, (b) Three Islands Granite, and (c) The Wolves Granite. Details of the analytical results and sample locations will be published elsewhere.

Dated sample NB00-40 is medium-grained quartz monzodiorite from the area of the dock on East Wolf Island. This rock type was selected for dating because of its large extent, at least on the northwestern side of the island, and relative homogeneity. The sample has hypidiomorphic inequigranular texture, and consists mainly of large subhedral plagioclase crystals with interstitial K-feldspar and quartz. Biotite and amphibole form about 15% of the rock. Relict orthopyroxene forms cores in some amphibole grains. Apatite and opaque minerals are relatively abundant accessory phases. The minerals show little alteration.

Zircon grains separated from sample NB00-40 were mainly large prisms, allowing for the analysis of single- and two-grain fractions. One analyzed grain was brown and slightly metamict. This grain contained high U and radiogenic Pb concentrations and was severely discordant (Figure 2c). Two other fractions consisted of single prismatic grains, whereas a third fraction consisted of two fragments of prismatic grains. All four analyses form a discordant trend with an upper intercept of 436.8±4.8 Ma, which we interpret as the time of crystallization of the quartz monzodiorite.

REGIONAL IMPLICATIONS

The ca. 618 and 611 Ma ages of the Ingalls Head Formation and Three Islands Granite on Grand Manan Island suggest affinity to the Avalon terrane of the northern Appalachian orogen, which is characterized by volcanic and plutonic rocks of similar ages, as well as younger Neoproterozoic rocks. Based on age alone, the Ingalls Head Formation may be part of the Broad River Group of the Caledonia terrane. However, the lithological features reported by Fyffe and Grant (2001) are not typical of the Broad River Group (Barr and White 1999). The age of ca. 611 Ma from the Three Islands Granite is slightly younger than most dated granitic units associated with the Caledonia terrane. The age suggests that correlation with ca. 609–605 Ma units in the Cobequid Highlands of northern mainland Nova Scotia (Figure 1) is another possibility (Pe-Piper and Piper, in press). These uncertainties may be resolved by additional U–Pb dating, as well as more detailed field and petrological work now in progress on Grand Manan Island.

The age of 437±5 Ma for granodiorite on East Wolfe Island shows that the previous interpretation (Barr *et al.* 2001) that granitoid rocks on The Wolves Islands are Neoproterozoic to Cambrian, based on their apparent petrological similarity to plutons of that age in the Brookville terrane, is not correct. It is, therefore, not clear that the Brookville terrane can be extended beyond Lepreau Harbour into the Bay of Fundy. The result again emphasizes the substantial uncertainty involved in making correlations between rock units based on appearance. Granitoid rocks of ca. 437 Ma age have not been found in the Caledonian Highlands (Barr and White 1999), so correlation with the Caledonia terrane (Figure 1) is unlikely. The ca. 437 Ma age is older than the Saint George Batholith and plutons of the Coastal Maine magmatic province, oldest components of which have ages of ca. 422 Ma (e.g., McLeod *et al.* 1994; Hogan and Sinha 1989). However, the age is similar to the age of volcanic and plutonic units in the Kingston terrane (Barr *et al.* 2002), although the rocks themselves do not appear similar. More work on field relations and petrology of the rocks on The Wolves Islands is essential to see if they are consistent with this correlation.

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GEOLOGY OF THE KEDGWICK, GOUNAMITZ RIVER, STATES BROOK AND MENNEVAL MAP AREAS (NTS 21 O/11, 21 O/12, 21 O/13 AND 21 O/14), RESTIGOUCHE COUNTY, NEW BRUNSWICK †

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CARROLL, J.I. 2003. Geology of the Kedgwick, Gounamitz River, States Brook and Menneval map areas (NTS 21 O/11, 21 O/12, 21 O/13 and 21 O/14), Restigouche County, New Brunswick. *In* Current Research 2002. *Edited by* B.M.W. Carroll. New Brunswick Department of Natural Resources; Minerals, Policy and Planning Division, Mineral Resource Report 2003-4, pp. 23–57.

The Kedgwick, Gounamitz River, States Brook and Menneval map areas are underlain by a Middle Paleozoic sedimentary succession that constitutes part of the Gaspé Belt of the northern Appalachians. The study area is divisible into five lithostratigraphic units: (1) the Late Ordovician Grog Brook Group, (2) the Late Ordovician to Early Silurian Matapédia Group, (3) the Early to Late Silurian Perham Group, (4) the Early Devonian Fortin Group, and (5) the Early to Middle Devonian Gaspé Sandstones Group. The Grog Brook Group comprises deep-water siliciclastic rocks that include the lowermost Boland Brook Formation and the conformably overlying Whites Brook Formation. The Ritchie Brook Member comprises carbonaceous shale that is located at the top of the Boland Brook Formation. Conformably overlying the Grog Brook Group, the Matapédia Group is composed of calcareous siliciclastic rocks of the lower Pabos Formation that are conformably overlain by carbonate mudrocks of the White Head Formation. The Perham Group comprises the newly named *Gounamitz Lake Formation* that is conformable with the underlying White Head Formation. The lower part of the Gounamitz Lake Formation is dominated by medium-bedded calcareous and quartzose sandstone; whereas, the upper part comprises mainly thin-bedded, calcareous and locally graptolite-bearing (possibly Ludlow age) sandstone and red shale. The Fortin Group comprises the newly named *Tracey Brook Formation* and the Temiscouata Formation. The Tracey Brook Formation is lithologically similar to the upper part of the Gounamitz Lake Formation and contains graptolites and chitinozoa indicative of a Pridolian–Lochkovian age. The basal part of the unit is in fault-contact with the Gounamitz Lake Formation along the Restigouche Fault. The Temiscouata Formation comprises a lower noncalcareous siltstone and sandstone member and a thin upper calcareous member composed of strongly calcareous siltstone and minor sandstone. The Gaspé Sandstones Group comprises noncalcareous sandstone and siltstone with locally abundant terrigenous organic matter of the York Lake Formation. Elsewhere, the group is interpreted to conformably overlie the Fortin Group but, in the study area, it lies in fault contact with the Temiscouata Formation along the Sainte-Florence Fault.

Two regional tectonic events are recognized in the study area. Northwest-trending open folds, attributed to the Siluro-Devonian Salinic event, are developed in the Ordovcian to Early Silurian Grog Brook and Matapédia groups. They are overprinted by northeast-trending, open to locally isoclinal folds and large-scale dextral strike-slip faults associated with the Middle to Late Devonian Acadian Orogeny. The McKenzie Gulch, Restigouche–Lower Downs Gulch and Sainte-Florence Fault zones were primarily active during the Acadian Orogeny and are mainly responsible for the current distribution of the rock units in the study area.

The effects of Siluro-Devonian Salinic tectonism are recognized only in northwest-trending open folds developed in rocks of the Grog Brook and Matapédia groups. Convincing synsedimentary evidence corresponding to the Salinic event, such as an unconformity or definitive shallow-water deposition, is absent in the study area. However, a late Early Devonian

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regressive event is recognized in the transition from the Temiscouata Formation to the organic-matter-bearing York Lake Formation. Therefore, a record of continuous sedimentation from the Late Ordovician to the late Early Devonian is indicated.

Les secteurs cartographiques de Kedgwick, de la rivière Gounamitz, du ruisseau States et de Menneval reposent sur une succession sédimentaire du Paléozoïque moyen qui constitue une partie de la ceinture de Gaspé dans le nord des Appalaches. Le secteur d'étude peut être subdivisé en cinq unités lithostratigraphiques : 1) le groupe de l'Ordovicien tardif du ruisseau Grog, 2) le groupe de l'Ordovicien tardif au Silurien précoce de Matapédia, 3) le groupe du Silurien précoce à tardif de Perham, 4) le groupe du Dévonien précoce de Fortin et 5) le groupe des grès du Dévonien précoce à moyen de Gaspé. Le groupe du ruisseau Grog est constitué de roches silicoclastiques d'eaux profondes comprenant la Formation de Boland Brook, formation la plus basse, et la Formation de White Brook, qui la recouvre de façon concordante. Le membre du ruisseau Ritchie est constitué de schiste charbonneux se trouvant au sommet de la Formation de Boland Brook. Le groupe de Matapédia, qui recouvre de façon concordante le groupe du ruisseau Grog, est composé de roches silicoclastiques calcaires de la Formation inférieure de Pabos, elles-mêmes recouvertes en concordance d'argiles schisteuses carbonatées de la Formation de White Head. Le groupe de Perham englobe la formation récemment baptisée *Formation de Gounamitz Lake*, qui est concordante avec la Formation sous-jacente de White Head. Du grès calcaire et quartzeux en strates moyennes prédomine dans la partie inférieure de la Formation de Gounamitz Lake, tandis que la partie supérieure est principalement constituée de schiste rouge et de grès (remontant possiblement au Ludlovien) calcaire et renfermant localement des graptolites, en strates minces. Le groupe de Fortin se compose de la formation nouvellement baptisée *Formation de Tracey Brook* et de la Formation de Témiscouata. La Formation de Tracey Brook est semblable par sa lithologie à la partie supérieure de la Formation de Gounamitz Lake et elle renferme des graptolites et des *chitinozoa* révélant qu'elle remonte au Pridoli–Lochkovien. La partie basale de l'unité se trouve en contact faillé avec la Formation de Gounamitz Lake le long de la faille de Restigouche. La Formation de Témiscouata comprend un membre inférieur de grès et de siltstone non calcaire et un membre supérieur mince calcaire composé d'une petite quantité de grès et de siltstone fortement calcaire. Le groupe de grès de Gaspé se compose de siltstone et de grès non calcaire ainsi que de matières organiques terrigènes localement abondantes de la Formation de York Lake. Ailleurs, le groupe recouvre, selon les interprétations, le groupe de Fortin de façon concordante, mais, dans le secteur d'étude, il est juxtaposé en contact faillé avec la Formation de Témiscouata le long de la faille de Sainte-Florence.

Deux phénomènes tectoniques régionaux sont reconnus dans le secteur d'étude. Des plis ouverts orientés vers le nord-ouest, attribués à un phénomène salinique du Siluro-Dévonien, sont apparus dans les groupes de l'Ordovicien au Silurien inférieur du ruisseau Grog et de Matapédia. Des plis ouverts devenant localement isoclinaux et des décrochements dextres à grande échelle, associés à la phase acadienne du Dévonien moyen à tardif, y sont superposés en direction nord-est. Les zones de la ravine McKenzie, de la ravine Restigouche–Lower Downs et de la faille de Sainte-Florence étaient essentiellement actives pendant la phase acadienne et elles constituent les principales zones responsables de la distribution actuelle des unités rocheuses dans le secteur d'étude.

On ne reconnaît les effets du diastrophisme salinique du Siluro-Dévonien que dans les plis ouverts orientés vers le nord-ouest qui se sont formés dans les roches des groupes du ruisseau Grog et de Matapédia. Le secteur d'étude est dépourvu de preuve synsédimentaire convaincante témoignant du phénomène salinique, comme une discordance ou une sédimentation définitive en eaux peu profondes. On reconnaît toutefois qu'une régression tardive est survenue au cours du Dévonien inférieur dans l'intervalle de transition de la Formation de Témiscouata à la Formation riche en matières organiques de York Lake. On dispose par conséquent d'un registre de sédimentation continu de l'Ordovicien tardif jusqu'à la fin du Dévonien inférieur.

INTRODUCTION

Geological investigations are nearing completion under the Appalachian Foreland and St. Lawrence Platform NATMAP project, a joint federal/provincial programme aimed at improving the current knowledge of the geological history and mineral/hydrocarbon potential of the Gaspé Belt in Québec and adjacent New Brunswick. In northwestern New Brunswick, geological studies were conducted during 1999, 2000, 2001 and 2002 in the Kedgwick, Menneval, States Brook and Gounamitz River areas, respectively, and have provided insight into the geological history of the Gaspé Belt. This report constitutes a summary and describes the general geology of the four map areas. A more detailed report is forthcoming upon completion of the project.

REGIONAL GEOLOGY

The rocks underlying the Kedgwick (NTS 21 O/11), Gounamitz River (21 O/12), States Brook (21 O/13) and Menneval (21 O/14) map areas (Figures 1 and 2) comprise an assemblage of siliciclastic and calcareous rocks deposited in outer shelf and slope environments during the Late Ordovician to the onset of the Early to Middle Devonian Acadian Orogeny. Collectively, they constitute part of the Gaspé Belt that extends from northern Maine through northwestern New Brunswick to the eastern tip of the Gaspé Peninsula in Québec. The Gaspé Belt forms a "cover sequence" laid down in a successor basin that formed during, and in response to, the closure of the Palaeozoic Iapetus Ocean and concomitant docking of the Gondwanan and Laurentian Margins (Malo and Bourque 1993; van Staal and de Roo 1995). The surface distribution of strata in the basin is subdivided into three tectonostratigraphic domains: (1) the Early Silurian to Middle Devonian, Chaleurs Bay Synclinorium; (2) the Late Ordovician to Early Silurian Aroostook–Percé Anticlinorium; and (3) the Late Silurian to Middle Devonian Connecticut Valley–Gaspé Synclinorium (Bourque *et al.* 1995) (Figure 1). Regionally, the domains are interpreted to be conformable (Malo 1988). In northern New Brunswick, the western margin of the Aroostook–Percé Anticlinorium is in fault contact with the Connecticut Valley–Gaspé Synclinorium along the Restigouche Fault and the eastern contact is, in places, conformable and, in other places, in fault contact with the Chaleurs Bay Synclinorium along the Rocky Brook–Millstream, McKenzie Gulch and Sellarsville faults.

The Chaleurs Bay Synclinorium lies immediately west of the Miramichi Terrane of Fyffe and Fricker (1987) and is predominantly underlain by Silurian rocks of the Chaleurs Group and Lower Devonian rocks of the Tobique and Dalhousie groups. However, some older rocks crop out in the Chaleurs Bay Synclinorium including the Ordovician Balmoral, Grog Brook, and Matapédia groups, which are exposed in and around the Popelogan Anticline. Most of the Chaleurs Group lies north of the Rocky Brook–Millstream Fault and can be traced into southern Gaspé, where the type-area is located. It comprises a varied assemblage of siliciclastic, carbonate and volcanic rocks of Llandoverian to Lochkovian age and occupies an equivalent stratigraphic position to the Perham Group in the Aroostook–Percé Anticlinorium to the west. The Chaleurs Group is conformably to disconformably overlain by the Dalhousie Group north of the Rocky Brook–Millstream Fault. South of this fault, the Tobique Group overlies the Chaleurs Group. Both the Dalhousie and Tobique groups comprise subaerial to shallow marine, mafic to felsic volcanic rocks intercalated with siliciclastic sediments.

The Aroostook–Percé Anticlinorium lies west of the Chaleurs Bay Synclinorium and comprises Middle Ordovician to Upper Silurian rocks of the Grog Brook, Matapédia and Perham groups. In the east, the Aroostook–Percé Anticlinorium is, at surface, along most of its length, in fault contact with the Chaleurs Bay Synclinorium along the McKenzie Gulch Fault except near the Restigouche River where it conformably underlies the Chaleurs Bay Synclinorium (Figure 1). In the west, it is in fault contact with the Connecticut Valley–Gaspé Synclinorium along the Restigouche Fault. The Grog Brook Group (St. Peter 1978) consists of deep-water turbidite deposits and equivalent rocks

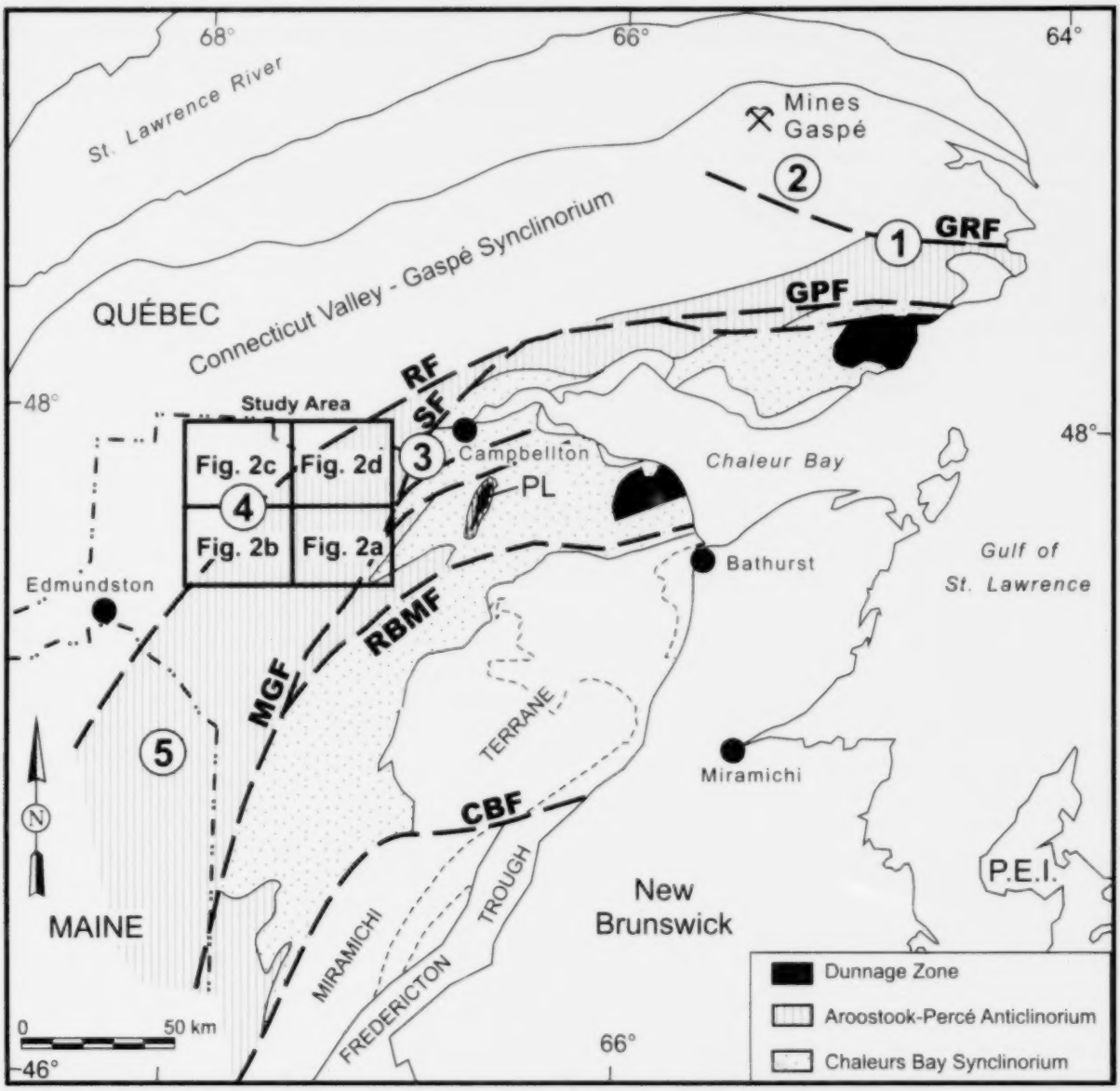

Figure 1. Major geological zones of the Gaspé Peninsula and northern New Brunswick showing the location of the study area and Figure 2. Abbreviations: **CBF** – Catamaran Brook Fault, **GPF** – Grand Pabos Fault, **GRF** – Grande Rivière Fault, **MGF** – McKenzie Gulch Fault, **PL** – Popelogan Inlier (Dunnage Zone), **RBMF** – Rocky Brook–Millstream Fault, **RF** – Restigouche Fault, **SF** – Sellarsville Fault. Circled numbers indicate section locations (Figure 11).

that can be traced northeastward into Gaspé Peninsula and southwestward into Maine. In the Gaspé Peninsula the Garin Formation (Riva and Malo 1988) is interpreted to be the correlative unit; at least to the lower part of the group. Toward the Maine–New Brunswick border, the Grog Brook is correlative with the "unnamed unit" of Hamilton-Smith (1970) and, in Maine, is correlative with the Madawaska Lake Formation of Roy and Mencher (1976). Significant lateral facies changes are apparent from northern New Brunswick to northern Maine.

The Matapédia Group (Alcock 1935) comprises deep-water carbonate and siliciclastic rocks that conformably overlie the Grog Brook Group. In northeastern Maine, Pavlides (1968) identified equivalent rocks as the Carys Mills Formation, a term also used by Hamilton-Smith (1970) in the Siegas area of northwestern New Brunswick. The Perham Group (Roy and Mencher 1976) predominantly consists of marine clastic rocks including minor red shale, which conformably overlie the Carys Mills Formation in northwestern Maine, and is subdivided into the lower New Sweden Formation (grey, calcareous siltstone and lesser red and green ferromanganiferous shale) and the upper Jemtland Formation (wacke, shale and local conglomerate and limestone).

The Connecticut Valley–Gaspé Synclinorium (Figure 1) underlies the northwestern part of New Brunswick and comprises siliciclastic rocks of the Fortin and Gaspé Sandstones groups. The Fortin Group mainly comprises deep-water mudstones. In Maine, the laterally equivalent unit is the Seboomook Formation (St. Peter 1978). In the Gaspé, the Fortin Group (no formations named therein) contains those rocks identified as Temiscouata Formation in New Brunswick (Bourque *et al.* 1995).

In eastern Gaspé, on the northern flank of the Connecticut Valley–Gaspé Synclinorium, the Gaspé Sandstones Group rests conformably on rocks of the Gaspé Limestones Group. The Gaspé Sandstones Group comprises shallow marine, variously calcareous sandstone, siltstone and limestone. The limestone is more common in the type-area in central Gaspé, becoming progressively less dominant toward the west. The underlying Gaspé Limestones Group is replaced to the west by the time-equivalent Fortin Group so that, in central Gaspé and northwestern New Brunswick, the Fortin Group conformably underlies the Gaspé Sandstones Group.

STRATIGRAPHY

Most of the study area is within the Aroostook–Percé Anticlinorium and Connecticut Valley–Gaspé Synclinorium (Figure 1), with the exception of the southeast corner of the Kedgwick map area (Figure 2a), which is underlain by calcareous siliciclastic rocks of the Silurian Upsalquitch Formation (St. Peter 1978)—part of the Chaleurs Group of the Chaleurs Bay Synclinorium. The Aroostook–Percé Anticlinorium comprises three lithostratigraphic units (Figures 2a, 2b, 2d): (1) the Upper Ordovician Grog Brook Group, (2) the Upper Ordovician to Lower Silurian Matapédia Group, and (3) the Silurian Perham Group. The oldest exposed rocks are in the Aroostook–Percé Anticlinorium, whereas the youngest rocks are in the Connecticut Valley–Gaspé Synclinorium in the western part of the study area. In the central part of the study area, rocks of the Perham Group conformably overlie the Matapédia Group (Figure 2b). The Connecticut Valley–Gaspé Synclinorium consists of Late Silurian to Early Devonian siliciclastic rocks of the Fortin and Gaspé Sandstones groups (Figure 2b, 2c).

Grog Brook Group

The Grog Brook Group, introduced by St. Peter (1978) without formal subdivision, is composed of deep-water siliciclastic turbidite deposits that are conformably overlain by siliciclastic and carbonate deposits of the Matapédia Group (Crickmay 1932; Lespérance *et al.* 1987). The base of the Grog Brook Group is not exposed in the study area but is thought to lie conformably (?) on shale of the Popelogan Formation (Balmoral Group) in the Popelogan Inlier to the east of the study area (Figure 1 and see Wilson 2000).

The first attempt at subdividing the Grog Brook Group was made by Carroll (2000). In that study the group was informally divided into a lower "mudstone-dominated" unit, a middle "carbonaceous shale" unit and an upper "sandstone-dominated" unit. Additionally, a separate basal unit was identified ("Pat Brook" beds) based on textural and compositional differences (see Carroll 2000).

LEGEND (Figures 2, 3, 4 and 5)

EARLY DEVONIAN

GASPÉ SANDSTONES GROUP

York Lake Formation

DYKs — Argillaceous limestone, sandstone and shale

FORTIN GROUP

Temiscouata Formation

DTC — Calcareous siltstone and sandstone (un-named)

DTC — Noncalcareous, micaceous siltstone and sandstone

Tracy Brook Formation

SDTBs — Calcareous sandstone and siltstone

EARLY - LATE SILURIAN

PERHAM GROUP

Gounamitz Lake Formation (SGLs)
Calcareous, siliceous sandstone and siltstone and red shale

CHALEURS GROUP

Upsalquitch Formation (SUPs)
Calcareous sandstone and siltstone

LATE ORDOVICIAN - EARLY SILURIAN

MATAPEDIA GROUP

White Head Formation

OSWHls — Limestone, calcareous shale

Pabos Formation

OPAls — Calcareous sandstone, shale and limestone

LATE ORDOVICIAN

GROG BROOK GROUP

Whites Brook Formation

OGWB — Sandstone and noncalcareous shale

Boland Brook Formation

OGBB — ← Ritchie Brook Member: Carbonaceous shale
Noncalcareous siltstone, shale and minor sandstone

SYMBOLS

Geological contact

Fault

Road

River or brook

D_1 plunging, D_1 syncline, D_1 anticline

D_2 plunging, D_2 syncline, D_2 anticline

Metamorphic aureole related to Patapedia intrusion

A' — A — Type area or reference section

Area of red shale within the Gounamitz Lake Formation

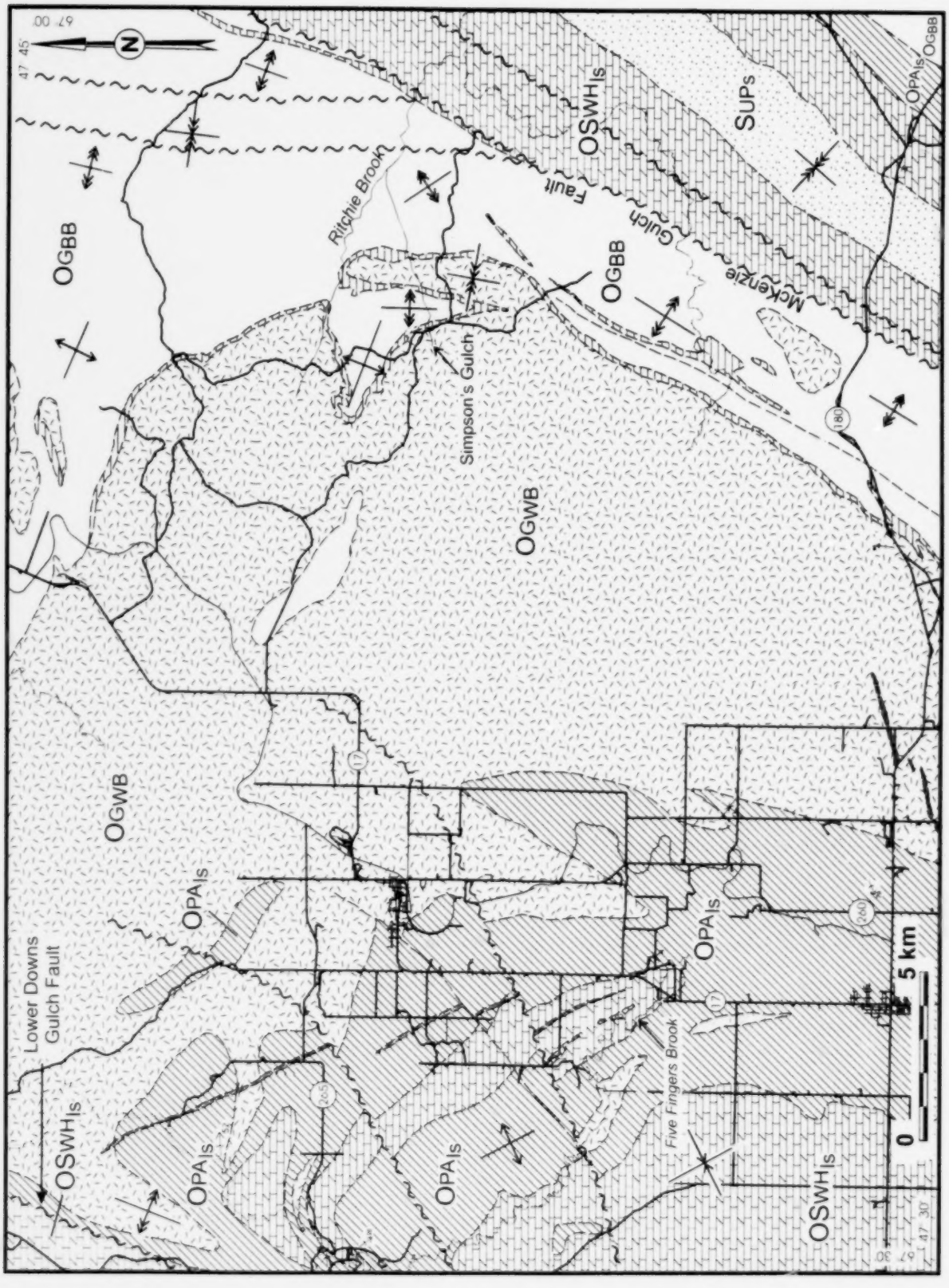

Figure 2a. Geological map of the Kedgwick map area (NTS 21 O/11). See legend for explanations.

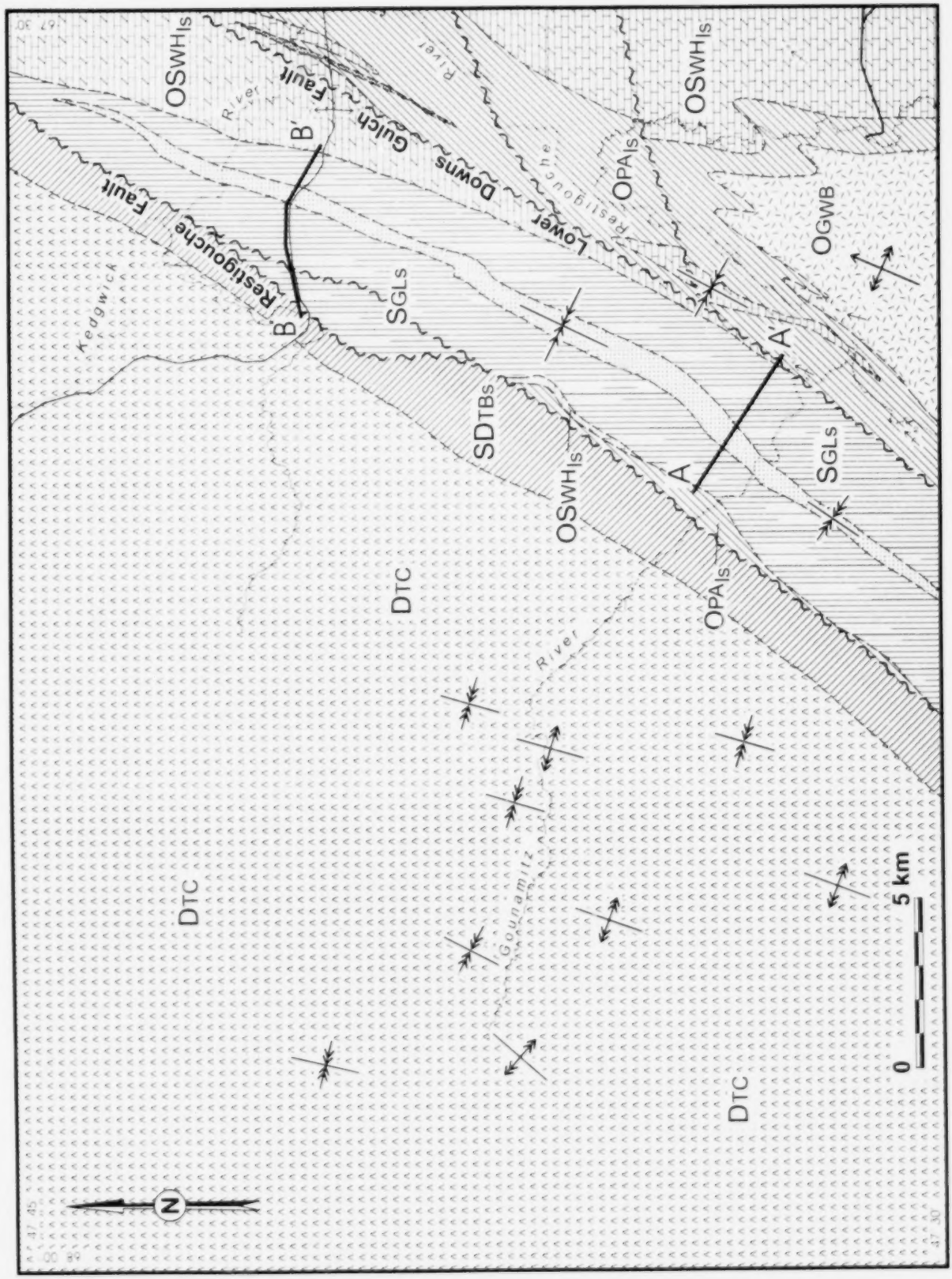

Figure 2b. Geological map of the Gounamitz River map area (NTS 21 O/12). See legend for explanations.

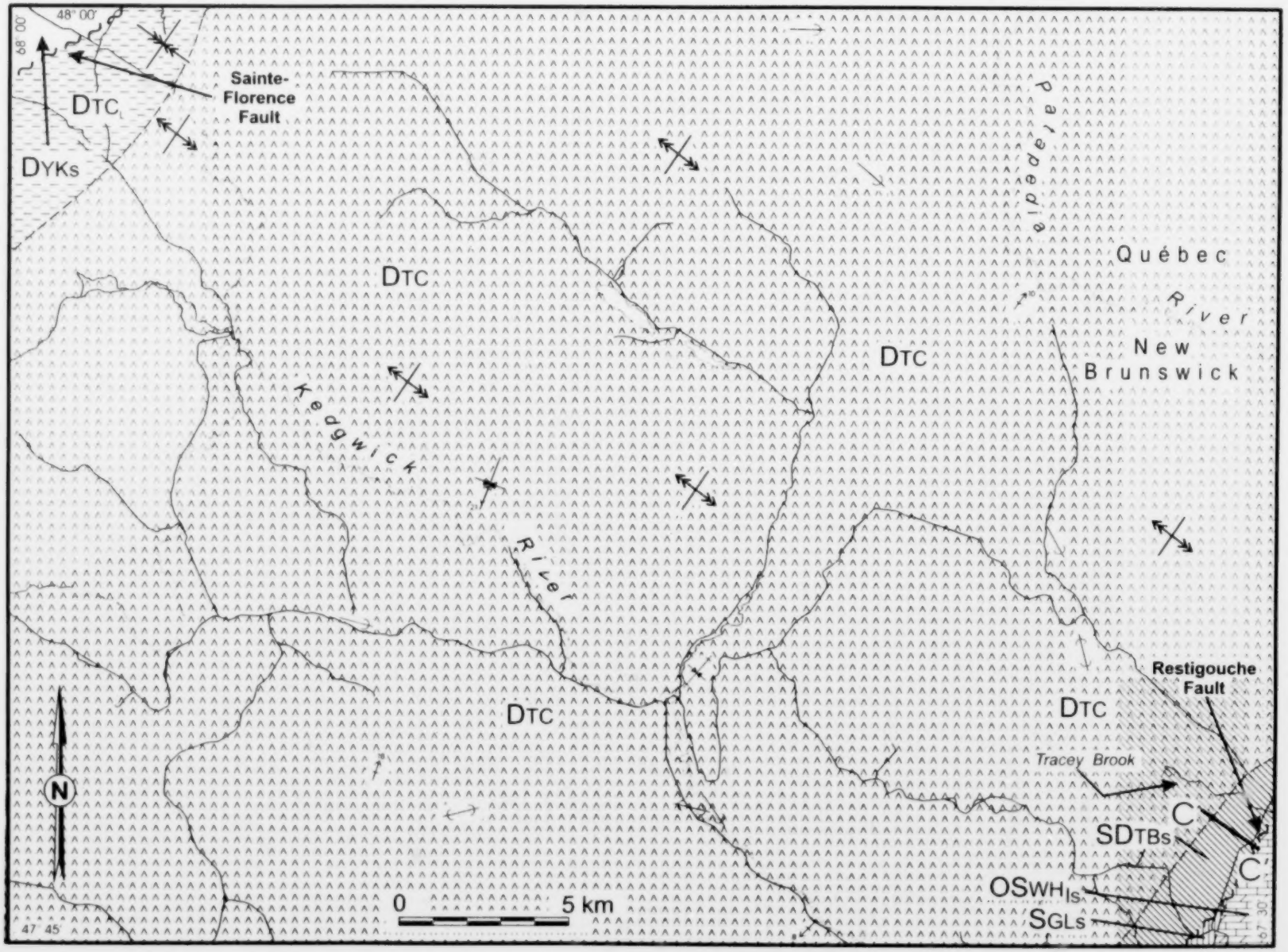

Figure 2c. Geological map of the States Brook map area (NTS 21 O/13). See legend for explanations. Geology northeast of the Patapédia River (Québec) adapted from Lachance (1993).

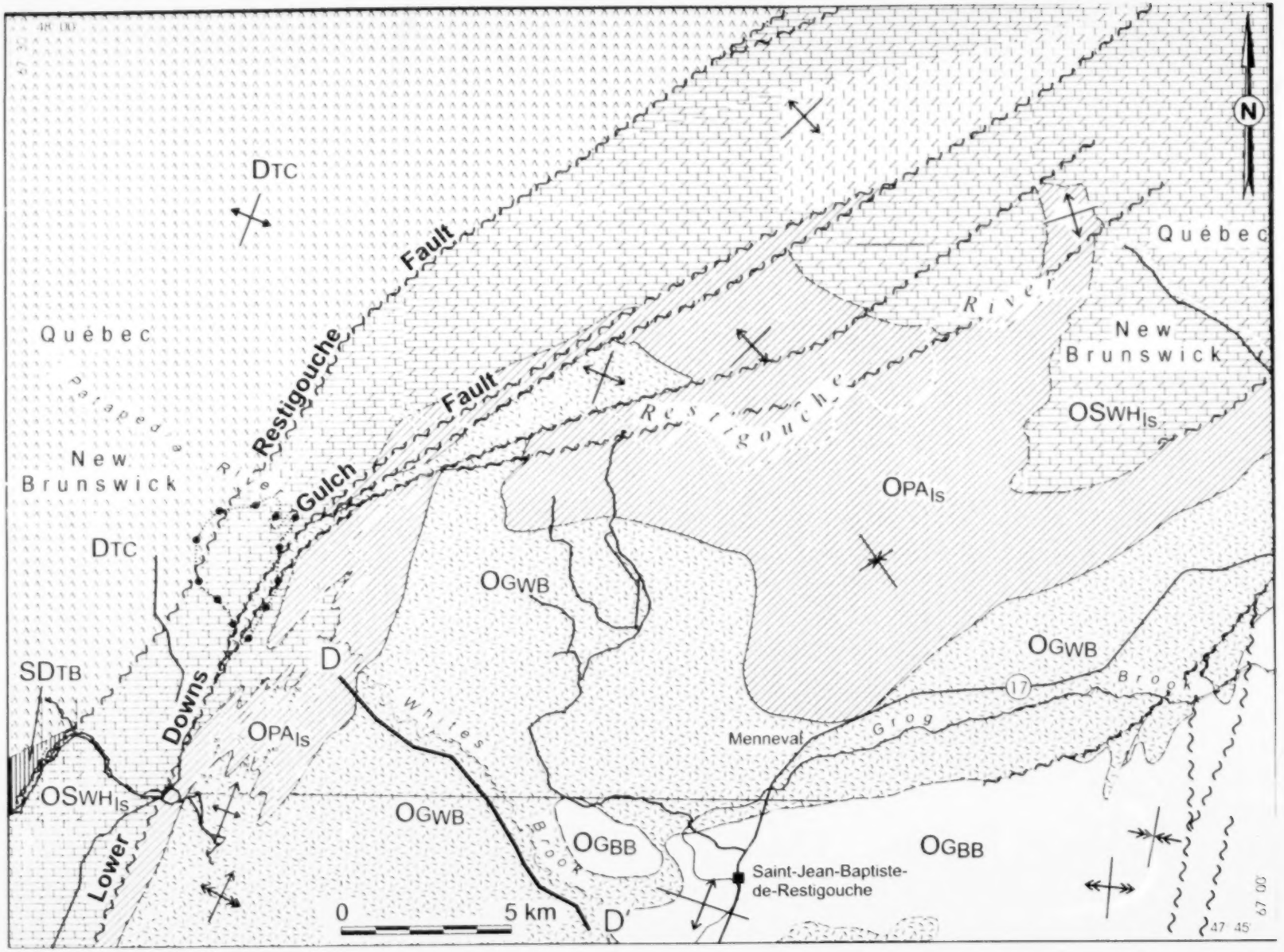

Figure 2d. Geological map of the Menneval map area (NTS 21 O/14). See legend for explanations. Geology north of the Restigouche River (Québec) adapted from Lachance (1993).

Wilson (2002) has introduced formal nomenclature such that the "mudstone-dominated" unit, the "carbonaceous shale" unit and the "Pat Brook" beds are assigned to the Boland Brook Formation and the "sandstone-dominated" unit is assigned to the Whites Brook Formation.

Boland Brook Formation

The Boland Brook Formation consists of grey–black to dark grey and locally greenish grey thin- to medium-bedded (5–20 cm) siltstone and shale interbedded with variable amounts of dark grey to medium grey, fine- to medium-grained sandstone (Figure 3). The sandstone is typically very thin-bedded (1–2 cm) although locally, beds may attain 20–30 cm in thickness. In the Kedgwick and Menneval map areas (Figures 2a, 2d), mudrock lithotypes typically make up 50% to 70% of the unit. Coarse-grained sandstone and polymictic conglomerate occur in the lower part of the formation to the east of the study area (Wilson 2002) and in the southeast corner of the Kedgwick map area, near Pat Brook (Figure 2a and see Carroll 2000). The coarse-grained sandstone and pebble conglomerate are moderately sorted, compositionally immature with subrounded to angular clasts of quartz, feldspar and rock fragments. The fine-grained lithotypes are noncalcareous; some sandstone beds are moderately calcareous on fresh surfaces. Flute casts are commonly present on the soles of the thicker sandstone beds indicating deposition by turbidity currents, although the typical thin-bedded, parallel- and cross-laminated, fine-grained sandstone suggests that deposition via contour flows was prevalent.

Thin laminae (1–3 mm) of black, carbonaceous hemipelagic mud are ubiquitous throughout the unit and are spaced from 10 to 30 cm apart. Near the upper contact with the Whites Brook Formation, the amount of carbonaceous mud increases rapidly and culminates in a 10 to 20 m thick, very thin-bedded (1– 2 cm), dark grey to black, moderately pyritic unit (see Carroll 2000 and Carroll 2002 for detailed descriptions). The unit is readily traceable via airborne electromagnetics (Carroll 2000) and good exposures of the unit are located in the east-central part of the Kedgwick map area along Ritchie Brook and Simpsons Gulch (Figure 2a). Because of the continuity of the unit, its chemical similarity (Carroll 2002) to the bulk of the Boland Brook Formation, and good exposure along Ritchie Brook (NTS 21 O/11), it is assigned the name Ritchie Brook Member.

The Boland Brook Formation is interpreted to gradationally overlie graphitic slate of the Popelogan Formation, which forms part of the Balmoral Group that crops out approximately 30 km to the east of the study area (Figure 1 and see Wilson 2000). The base of the Boland Brook Formation is not exposed in the study area, precluding an estimate of the formation's thickness. However, work by St. Peter (1978), Carroll (2000) and Wilson (2002) indicate a minimum thickness of 1600 to 2000 m; the upper 1200 m being overwhelmingly dominated (70–80%) by mudrocks.

The age of the Boland Brook Formation is inferred based on lithostratigraphic correlation. In Quebec, the lithologically similar Garin Formation possesses a late Caradocian to early Ashgillian graptolite fauna (Riva and Malo 1988) and east of the study area in the Sewells Gulch area, a chitinozoan microfauna from the Boland Brook Formation indicates an early Ashgillian age (Richmondian) (Asselin, written communication 2002).

Whites Brook Formation

The Whites Brook Formation comprises fine- to medium-grained, medium light grey to medium dark grey, thin- to thick-bedded (5 to > 60 cm), variously micaceous, weakly to moderately calcareous sandstone interbedded with predominantly noncalcareous, medium to dark grey, thin- to thick-bedded (3 to >25 cm) siltstone and lesser shale. Bedforms such as full and partial Bouma sequences, flute casts and scours, typical of deposition via turbidity currents, are much better developed than in the underlying Boland Brook Formation, suggesting deposition in a submarine channel and fan

Figure 3. Mudrocks (dark) and thin-bedded sandstone of the Boland Brook Formation. Hammer head is 20 cm in length.

Figure 4. Thick-bedded sandstone of the Whites Brook Formation.

environment (Figure 4). Locally, coarse-grained sandstones and pebbly, polymictic conglomerates are present, indicating the locus of palaeochannels. Volumetrically, the sandstone lithotype predominates (approximately 60%) although siltstone and shale are more abundant in some sections; the latter are interpreted as overbank deposits within the submarine fan assemblage. The fine- to medium-grained sandstone is weakly to moderately calcareous when fresh, reflecting the presence of calcareous cement and minor detrital carbonate. The coarse-grained sandstone and conglomerates tend to be less calcareous. The latter observation may, in part, reflect deeper weathering associated with the increased porosity of the coarse-grained rocks. The sandstone and siltstone of the Whites Brook Formation are generally lighter in colour (Munsell N-3 to Munsell N-6) than similar sandstone and siltstone of the underlying Boland Brook Formation (Munsell N-2 to N-4). Pebble conglomerates are typically lighter in colour, better sorted, and are compositionally and texturally more mature than those observed within the underlying Boland Brook Formation.

The upper and lower contacts of the Whites Brook Formation are conformable with the Pabos (Matapédia Group) and Boland Brook formations, respectively. The lower contact with the Ritchie

Brook Member of the Boland Brook Formation is typically sharp and in the Kedgwick map area (Figure 2a) is placed beneath the first thick-bedded, medium- to coarse-grained sandstones. In the Menneval map area (Figure 2d), the contact with the Boland Brook Formation is established where, upon ascending the section, mudrocks make up less than 50 % of the section, carbonaceous laminae appear only locally, and sandstone beds are consistently greater than 15 cm thick. The upper contact with the Pabos Formation is defined where the noncalcareous mudrocks of the Whites Brook become weakly calcareous.

The thickness of the Whites Brook Formation is estimated at 4000 m based on good exposure in the type area along Whites Brook (Figure 2d, section D—D'). No correlative unit is identified in Gaspé Peninsula, although there are some similarities with the coarse-grained facies of the Pabos Formation.

The age of the Whites Brook Formation is considered to be middle Ashgillian (middle Richmondian) based on chitinozoan fauna located east of the Menneval map area (Wilson 2002) and is in good agreement with the early Ashgillian age for the top of the Garin Formation in Gaspé Peninsula (Riva and Malo 1988).

Matapédia Group

St. Peter (1978) identified the Matapédia Group within the study area but left it undivided. In the type area in eastern Gaspé, the group comprises the Pabos and White Head formations (Lespérance *et al.* 1987). Malo (1988) further refined the subdivisions of the group in Gaspé Peninsula. Their nomenclature is adopted herein, although their subdivisions of the White Head Formation could not be mapped because of poor exposure and complex tectonic deformation. The reader may find detailed descriptions of the White Head Formation in Bourque *et al.* (1995), Malo (1988) and Lespérance *et al.* (1987).

Pabos Formation

The Pabos Formation comprises light grey to dark grey, medium- to thin-bedded, fine- to coarse-grained, calcareous sandstone interbedded with dark grey, calcareous siltstone, shale and minor conglomerate (Figure 5). The bedding thickness gradually decreases from the bottom of the unit (20 to >30 cm) to the top (5–20 cm). The base of the Pabos Formation closely resembles the underlying Whites Brook Formation except for the higher carbonate content in the former (compare Figures 4 and 5). Sandstone predominates in the lower part of the Pabos section (approximately 60 %) and bedforms (Bouma sequences and flute casts) indicate deposition by turbidite flows in a submarine fan environment. Higher in the stratigraphy, toward the overlying White Head Formation, the bed thickness and sandstone content gradually diminish; the former varying from 5 to 20 cm, the latter decreasing to approximately 30% and calcareous siltstone becomes dominant. The thin-bedded, calcareous siltstone is prevalent in the north-central part of the Menneval map area adjacent to the Restigouche River (Figure 2d), whereas along Whites Brook, the more thickly bedded, sandstone-dominated facies predominates (Figure 2d). Near the top of the unit, thin beds of dark bluish grey, argillaceous limestone (calcilutite) begin to appear marking the transition between the Pabos and White Head formations (Figure 6).

The presence of tight folding combined with poor exposure of the upper and lower contacts precludes a definitive estimation of the thickness of the Pabos section, but is in excess of 1000 m based on exposures along Whites Brook (Figure 2d). Bourque *et al.* (1995) indicate a 3000 m thickness for the Pabos Formation in central Gaspé.

Figure 5. Calcareous sandstone of the Pabos Formation. Note the tight folding. Scale is in centimetres.

Figure 6. Fine-grained Pabos Formation near the overlying White Head Formation. Note the boudinaged calcilutite bed (with white calcite infillings) in the center. Hammer is 40 cm in length.

Figure 7. Medium-bedded, bluish grey calcilutite, typical of the White Head Formation. Bedding is subvertical.

Conodont assemblages (Nowlan 1983) and graptolite faunas (Riva and Malo 1988) collected along the Restigouche River immediately east of the Menneval map area (Figure 2d) indicate ages of late Ashgillian and middle Ashgillian, respectively.

White Head Formation

The White Head Formation is composed of mainly thin- to medium-bedded (5–25 cm) and laminated, dark bluish grey argillaceous limestone (calcilutite) interbedded with thin-bedded (2–10 cm), medium dark grey to dark grey calcareous sandstone, siltstone and minor shale (Figure 7). The calcilutite typically makes up approximately 70% to 80% of the unit. Locally, the White Head Formation contains relatively thick (20–30 m) sections of dark grey to greyish green, variously calcareous, siltstone and shale. Elsewhere, similar shale constitutes the "middle slate member" (Carys Mills Formation) of Hamilton-Smith (1970), the "middle shale member" of St. Peter (1978) and the Côte de la Surprise member of Lespérance *et al.* (1987), all of which occupy a medial stratigraphic position within the White Head Formation. The most distinctive feature of the White Head Formation is its differential weathering, in which calcilutite beds weather light grey in positive relief whereas interbedded siltstone weathers tan–brown in negative relief giving the rock a "ribboned" appearance.

The lower contact of the White Head Formation is conformable and gradational with the more terrigenous Pabos Formation and is generally defined, upon ascending the section, as that point where calcilutite becomes predominant; a transition that occurs over tens or hundreds of metres. The upper contact with the Perham Group is exposed along the Kedgwick River (Figure 2b, section B—B') and is interpreted to be conformable based on the observation that calcilutite, typical of the White Head, is interbedded with sandstones typical of the overlying Gounamitz Lake Formation with the calcilutite content rapidly decreasing up-section. The White Head Formation is in fault contact with the Perham Group along 6 km of the Lower Downs Gulch Fault in the southern part of the Gounamitz River map area (Figure 2b, section A—A').

The true thickness of the White Head Formation is difficult to establish in the map area because of tight upright folding, but probably exceeds 2000 m. St. Peter (1978), Malo (1988) and Wilson (2002) indicate thicknesses of approximately 2800 m in the Restigouche River area, 150–4000 m in the central Gaspé area, and 1200 m in the Chaleurs Bay area, respectively. The thickest sections occur in eastern Gaspé and generally become thinner toward central Gaspé and New Brunswick (Malo 1988).

Several long-ranging conodont assemblages (Ashgillian to Llandoverian) have been identified along a section of the Restigouche River (Nowlan 1983) and elsewhere equivalent rocks have an age that is relatively well constrained from Ashgillian to Llandoverian with an upper age limit of Llandoverian C3–C4 (Pavlides 1968; Hamilton-Smith 1970; Riva and Malo 1988; Malo 1988; Bourque *et al.* 1995; Wilson 2002).

Chaleurs Group

The Chaleurs Group in northern New Brunswick comprises ten formally named units (Walker and McCutcheon 1995); however, only the Upsalquitch Formation is recognized in the study area, where it was first identified by St. Peter (1978). The Upsalquitch Formation is the lowermost unit of the Chaleurs Group and comprises a sequence of calcareous and siliciclastic sandstones and mudrocks.

Upsalquitch Formation

The Upsalquitch Formation occupies the core of a tight, upright, northeast-trending syncline in the southeast corner of the Kedgwick map area (Figure 2a). The formation comprises thin-bedded (1–3 cm), calcareous and locally micaceous, fine-grained sandstone and calcareous siltstone interbedded with fine- to coarse-grained, thin- to thick-bedded (10–30 cm) calcareous sandstone. The coarse-grained sandstones have bedforms typical of turbidite deposits, displaying full and partial Bouma sequences and abundant basal load structures. In the Kedgwick map area, the thin-bedded facies makes up approximately 40% of the unit with turbidite sequences making up the remaining 60%. The fine-grained facies is lithologically very similar to a small part of the Gounamitz Lake Formation. Fossil debris occurs locally in the turbidite beds and comprises mixtures of crinoid ossicles, trilobite carapaces and small pieces of brachiopod shells in various proportions. The lower contact is not exposed in the area; however, thin beds of calcilutite are more common toward the base of the unit indicating a conformable contact with the underlying White Head Formation. These rocks are equivalent to the lowermost Arsenault Brook member of the Upsalquitch Formation, which has been described by Wilson (2000) for beds exposed 20 km northeast of the study area.

Although tightly folded, the thickness of the formation is estimated at 800–1000 m in the map area. This is approximately half the thickness of 1600 m at its type-area located approximately 30 km to the northeast of the Kedgwick map area (Wilson 2002).

The age of the Upsalquitch Formation is interpreted to range from early Llandoverian to early Wenlockian (St. Peter 1978; Irrinki 1990) based on brachiopod fauna.

Perham Group

Immediately south of the study area, St. Peter (1978) assigned a green slate and fine-grained sandstone unit, containing interbeds of red slate, to the "Perham Formation" a name introduced by Boucot *et al.* (1964) for rocks in northern Maine. In northwestern New Brunswick Hamilton-Smith (1970) identified an upper and lower "Perham Formation" that are equivalent to, respectively, the New Sweden and Jemtland formations of northeastern Maine (Roy and Mencher 1976). The New Sweden and Jemtland beds and underlying Siegas Formation (calcareous sandstone, siltstone and shale) are now considered to form the Perham Group near the New Brunswick–Maine border. Equivalent rocks in the study area are herein assigned a new name, the Gounamitz Lake Formation that conformably overlies the Ordovician to early Silurian Matapédia Group. It occupies a similar stratigraphic position as the Upsalquitch Formation of the Chaleurs Group (Figure 2 legend).

Gounamitz Lake Formation (new name)

The name, Gounamitz Lake Formation, is proposed for a greenish grey, calcareous, quartz-rich sandstone unit (Figure 8) that conformably overlies the White Head Formation in the Gounamitz River area (Figure 2b). The type-area is located along an unnamed logging road approximately 500 m north of Gounamitz River and 1500 m south of Gounamitz Lake (Figure 2b section A—A'). Another reference section is located approximately 6 km west of the confluence of the Kedgwick and Restigouche rivers along the Falls Brook Road (Figure 2b section B—B'). The unit occupies a syncline that extends through the central part of the Gounamitz River map area, northeast to the southeast corner of the States Brook map area, where it terminates against the Restigouche Fault (Figure 2c). The east and west contacts are considered to form the basal part of the unit.

The Gounamitz Lake Formation comprises light grey to greenish grey, medium- to thick-bedded, fine-grained, calcareous, quartzose sandstone and dark grey, thin-bedded, variously calcareous siltstone. The quartzose sandstone is volumetrically more significant (50–60%) in the basal half of

the unit and possesses weak lamination, no bioturbation and a distinct light brown, 5–15 cm, deep-weathering "rind" (Figure 8). Calcilutite beds occur locally near the contact with the underlying White Head Formation. Very minor bioturbated and calcareous mudrocks occur near the base of the formation. Higher in the section the more abundant sandstone gives way to thin- to medium-bedded, well laminated, fine- to medium-grained sandstone and siltstone (Figure 9) with very minor, very thin-bedded, maroon and green shale (Figure 10). The thin-bedded and laminated facies commonly contains graptolites (Figure 9). The western contact of the Gounamitz Lake Formation is everywhere in fault contact along the Restigouche Fault (Figure 2b).

The Gounamitz Lake Formation is assigned to the Perham Group rather than to the time-equivalent Chaleurs Group because of its closer lithological similarity to the former. The calcareous and quartzose sandstone-dominated (with interbedded calcilutite) basal part of the formation suggests correlation with calcareous and siliceous limestone of the New Sweden Formation in northern Maine (Siegas Formation in western New Brunswick), whereas the thin-bedded, graptolite-bearing facies and red shale in the upper part of the unit may be equivalent to the Jemtland Formation (Roy and Mencher 1976) (Figure 11, columns 4 and 5).

There are also some lithological similarities between rocks of the Gounamitz Lake Formation and those of the Upsalquitch (Wilson 2000), Burnt Jam Brook (Brisebois, personal communication, 2002), and Saint Leon formations (Chaleurs Group) (see Figure 11 for locations). For example, the upper and lower parts of the Gounamitz Lake Formation resemble the thin-bedded and thick-bedded facies of the Saint Léon Formation, respectively; whereas, the bioturbated calcareous mudrocks closely resemble similar facies of the Upsalquitch and Burnt Jam Brook formations (Figure 11, columns 2 and 3). However, the bioturbated mudrocks make up a very small proportion of the Gounamitz Lake Formation and occur only in the northern part of the formation's extent, near its truncation against the Restigouche Fault.

The thickness of the Gounamitz Lake Formation is difficult to establish in the States Brook map area as a result of its proximity to the Restigouche Fault zone. Gradually more of the section is cut out northward along the Restigouche Fault and about 2 km north of the southern boundary of the States Brook map area the entire formation is missing (Figure 2d). Investigations in the Gounamitz River map area (Figure 2b section A—A'), where the unit is more extensive, suggest a thickness in excess of 2000 m, which is in general agreement with an estimate of 2800 m by St. Peter (1978) for the "Perham Formation" in the Rivière Verte area, about 40 km southwest of Gounamitz River.

The lower age limit of the Gounamitz Lake Formation is well constrained because it comformably overlies the White Head Formation that is no younger than early Llandoverian. However, the upper age is less well defined. A mono-specific graptolite fauna collected from the Gounamitz River map area, in the upper part of the formation, has been tentatively assigned a Ludlovian age (Melchin, personal communication, 2002). Therefore, it could range in age from early Llandoverian to Ludlovian, which spans the age range of much of the Chaleurs Group (Figure 11), which is in agreement with ages obtained from the middle Perham near the Maine–New Brunswick border (St. Peter 1978).

Fortin Group

The name, Fortin Group, has not hitherto been applied to rocks in New Brunswick. McGerrigle (1943) originally applied the term "Temiscouata Group" to limestones and agglomerates in southern Québec. Lespérance and Greiner (1969) included the Beau Lac Formation and Temiscouata Series in the Devonian Temiscouata Formation and established a type-area near Nôtre-Dame-du-Lac close to the New Brunswick–Québec border. St. Peter (1978) extended the term to include all equivalent Lower Devonian strata in northwestern New Brunswick. The group underlies all of the central and western part of the States Brook and Gounamitz River map areas, respectively

Figure 8. Medium- to thick-bedded, tan-weathering, calcareous, quartzose sandstone of the lower part of the Gounamitz Lake Formation. Hammer is 40 cm in length.

Figure 9. Thin-bedded and laminated fine-grained sandstone of the upper part of the Gounamitz Lake Formation. This facies commonly contains graptolites. Hammer head is 2.5 cm in width.

Figure 10. Interbedded maroon and green shale of the Gounamitz Lake Formation. Hammer is 40 cm in length.

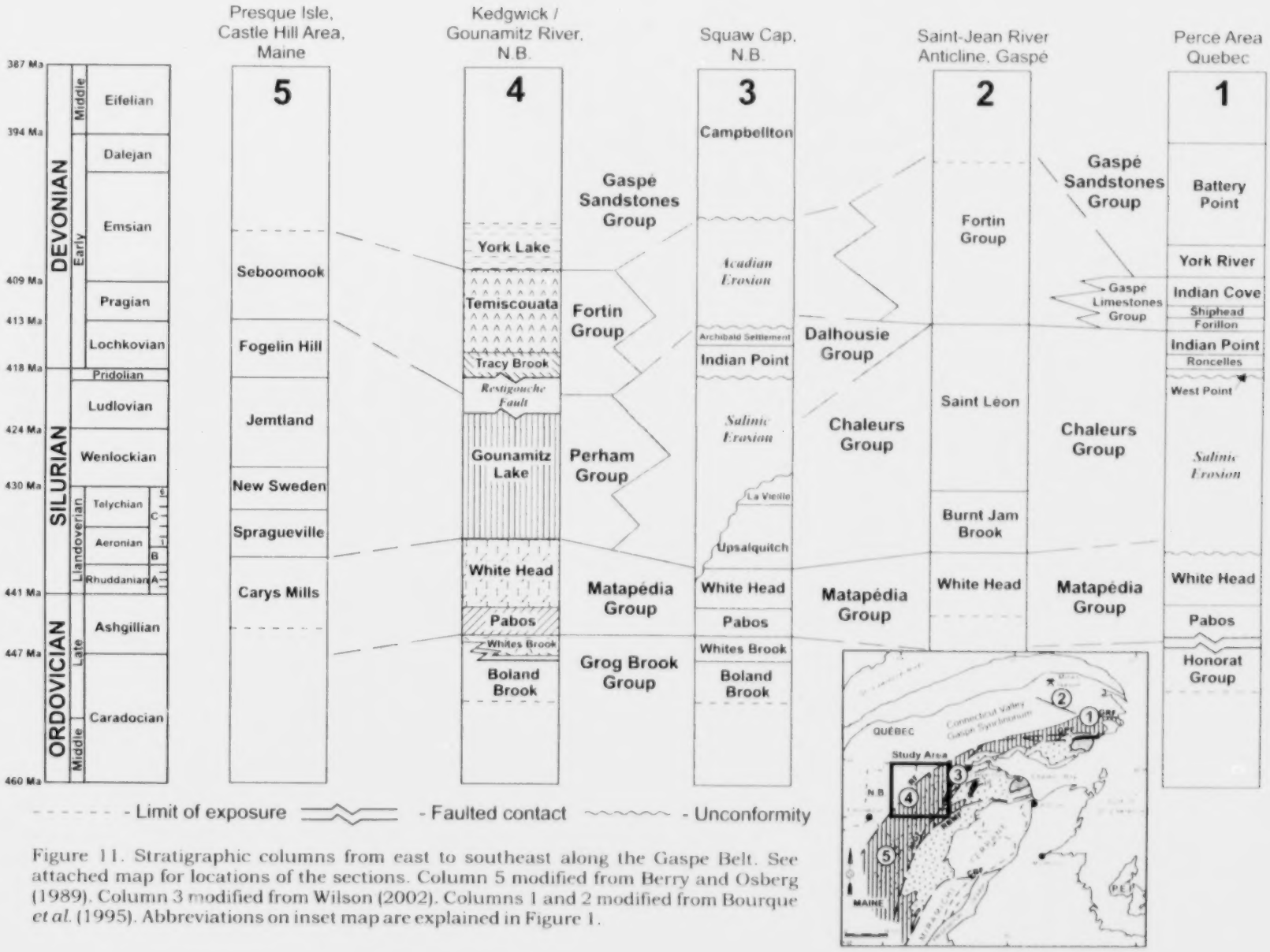

Figure 11. Stratigraphic columns from east to southeast along the Gaspe Belt. See attached map for locations of the sections. Column 5 modified from Berry and Osberg (1989). Column 3 modified from Wilson (2002). Columns 1 and 2 modified from Bourque *et al.* (1995). Abbreviations on inset map are explained in Figure 1.

Figure 12. Buff-weathering, medium-bedded sandstone of the Tracey Brook Formation. Note the similarity to Figure 9. Hammer is 40 cm in length.

(Figure 2b, 2c) and extends southwest to the Baker Lake area near Edmundston (Figure 1). In the study area, Temiscouata Formation rocks conformably overlie a distinctive buff-weathering sandstone unit north of the Restigouche Fault. The name, Tracey Brook Formation, is proposed for this sandstone unit. Both formations are assigned to the Fortin Group.

Tracey Brook Formation (new name)

The name, Tracey Brook Formation, is proposed for a tan- to buff-weathering sandstone unit that conformably underlies the Temiscouata Formation. The type-section is located along Tracey Brook 2 km east of Tracey Depot in the southeast part of the States Brook map area (NTS 21 O/13) (Figure 2c, section C–C'). Good reference exposures are also located along unnamed logging roads 500 m south of Tracey Brook and 500 m south of Gounamitz River (Figure 2b). In the study area, the formation extends from the south-central part of the Gounamitz River map area to the southwest corner of the Menneval map area (Figures 2b, 2c, 2d).

The Tracey Brook Formation comprises thin- to thick-bedded, grey to greenish grey, weakly calcareous, fine- to medium-grained sandstone interbedded with weakly to noncalcareous dark grey to dark green siltstone and shale (Figure 12). Minor thin beds of calcilutite occur locally. Sandstone typically makes up 60–70% of the observable section with mudrock lithotypes making up 30–40%. The sandstone commonly weathers tan to buff with a slight greenish tint. The mudrocks weather in a similar fashion but slightly darker. Internal structures are common and consist of

parallel lamination, cross lamination and minor convolute lamination. Thin-bedded, discontinuous maroon shale at the top of the formation is conformable with the Temiscouata Formation and resembles the older (?) maroon shale of the Gounamitz Lake Formation (Figure 13). Deposition by turbidity currents is inferred based on the occurrence of partial Bouma sequences and flute casts. Nowhere is there evidence of coarse-grained channel facies rocks. Graptolites are locally abundant in the fine-grained sandstone.

The Tracey Brook Formation, although similar in many respects to the upper part of the Gounamitz Lake Formation, is placed in the Fortin Group because of the conformable nature of its contact with, and similar age to, the base of the overlying Temiscouata Formation. Additionally, there is an unknown amount of stratigraphy missing along the Restigouche Fault (Figures 2b, 2c) that precludes an absolute correlation with the Perham Group (Gounamitz Lake Formation). A similar rationale has been employed by Wilson (2002) to assign the Indian Point Formation (Figure 11, column 3) to the Dalhousie Group (conformably underlying the Archibald Formation of the Dalhousie Group), whereas in Gaspé, the Indian Point Formation is placed in the Chaleurs Group where it constitutes the uppermost unit of the Chaleurs Group (Figure 11, column 1). The Tracey Brook Formation may be correlative to the Fogelin Hill Formation in the Jemtland area of Maine (Figure 11, columns 4 and 5) based on the latter's similar lithology and age (see Roy and Mencher 1976).

The faulted lower contact makes thickness estimation speculative; however, the observable section indicates a minimum thickness of 600–700 m for the Tracey Brook Formation. Graptolite fauna (*Monograptus microdon aksajensis*) from the middle part of the Tracey Brook Formation are indicative of a highest Pridolian to lowest Lochkovian age for the unit (Melchin, written communication, 2002). Additionally, a chitinozoa microfauna from the same location yielded a Lochkovian age (Asselin, written communication, 2002).

Temiscouata Formation

The Temiscouata Formation underlies most of the States Brook and Gounamitz River map areas (Figures 2b, 2c) and comprises two unnamed members. The lower and most voluminous one consists of a thick, assemblage of thin- to locally medium-bedded, grey black to dark grey, micaceous, weakly to non-calcareous slate and siltstone with interbedded, dark grey to medium grey, weakly calcareous, thin- to medium-bedded, micaceous sandstone (Figure 14). Minor polymictic pebble conglomerate occurs locally as 1–3 m thick beds in the western part of the States Brook map area (Figure 15). The formation weathers greyish brown to medium grey with the sandstone beds typically tan in colour. The sandstone is generally fine-grained and thin-bedded (1–5 cm); however, medium- to coarse-grained wacke and local arkosic beds are common. The coarse-grained beds are more abundant in the central part of the States Brook map area. Sandstone makes up approximately 30–50 % of the unit with siltstone and slate comprising 50–70 %. The upper contact is conformable and gradational (over a minimum distance of 500 m) with the calcareous member of the Temiscouata Formation.

The calcareous member comprises thin-bedded (1–10 cm), dark grey to blueish grey–black, micaceous and strongly calcareous siltstone and slate interbedded with medium grey to dark grey, strongly calcareous, fine-grained, thin-bedded and parallel-laminated sandstone (Figure 16). Weakly calcareous shale laminae (1–2 mm) occur locally. Mudrocks and sandstone make up approximately 70% and 30% of the unit, respectively. A well-developed cleavage, similar to that in the rest of the Temiscouata Formation, is present. The uppermost part of the unit lies in fault-contact with sandstones and mudrocks of the York Lake Formation (Gaspé Sandstones Group) along the Sainte-Florence Fault (Figure 2c). The best exposures of the member are located along several unnamed logging roads approximately 1 km west of the Kedgwick River, near the New Brunswick–Québec border.

Figure 13. Interbedded maroon and green shale of the Tracey Brook Formation. Hammer is 40 cm in length.

Figure 14. A moderately large synsedimentary slump-fold in thin-bedded siltstone and sandstone of the Temiscouata Formation. Note the well-developed, subvertical cleavage that cuts across the fold limbs from lower right to upper left. Scale in centimetres.

Figure 15. Polymictic pebble conglomerate of the Temiscouata Formation. Hammer head is 20 cm in length.

Figure 16. Thin-bedded, strongly calcareous siltstone and minor fine-grained sandstone of the Temiscouata Formation (*calcareous unit*) near the Sainte-Florence Fault. Note the synsedimentary slump fold and upright cleavage. Hammer head is 25 cm in length.

Soft-sediment slump folds at various scales are prevalent throughout much of the formation (Figure 14). A pervasive, subvertical cleavage (Figure 14) is preferentially developed in the Temiscouata Formation relative to adjacent formations. This cleavage is parallel to, or at low angles to the orientation of the Restigouche Fault. Dextral transpression associated with the fault has produced a series of tight, upright folds of variable wavelength (tens to hundreds of metres) with southeast and northwest vergences. The above factors make an estimation of thickness impossible in the study area. However, in the Squatec–Cabano area of Québec the unit's thickness has been estimated at 3700 m (Lespérance and Greiner 1969).

The lower contact of the Temiscouata Formation is conformable with the underlying Tracey Brook Formation from the south-central part of the Gounamitz River map area (Figure 2b) to the southwest corner of the Menneval map area (Figure 2d) where the Tracey Brook Formation is truncated against the Restigouche Fault. North of that point, the Temiscouata is in fault contact with White Head Formation rocks.

The age of the Temiscouata Formation is inferred from brachiopod fauna described by St. Peter and Boucot (1981) as Lower Devonian (Lochkovian to Emsian). This is in good agreement with the Pridolian–Lochkovian age from the conformably underlying Tracey Brook Formation. The upper age is constrained by the presence of the York Lake Formation in the northwest corner of the States Brook map area (Figure 2c), which is dated as Emsian on the basis of plant fragments and shelly fauna (Boucot and Johnson 1967).

Gaspé Sandstones Group

The "Gaspé Sandstones" sequence was originally defined by Logan (1863) in eastern Gaspé Peninsula and further subdivided by subsequent authors (see Bourque *et al.* 1995), resulting in introduction of the York Lake, York River, Battery Point and Malbaie formations and elevation of the name to group status. Rocks of this group have not been recognized previously in New Brunswick; however, in the northwest corner of the States Brook map area (Figure 2c), the rocks are assigned to the York Lake Formation, the lowermost unit in the Gaspé Sandstones Group (Figure 2c).

York Lake Formation

The York Lake Formation (McGerrigle 1950) crops out in the northwest corner of the States Brook map area (Figure 2c), where it comprises weakly to noncalcareous, greyish green to brownish green, thin- to medium-bedded, fine- to medium-grained feldspathic sandstone (Figure 17) and thin- to medium-bedded dark greyish green to dark grey, noncalcareous siltstone and shale. Locally the sandstones are cross-bedded and flaser-bedded, the intervening material consisting of fine-grained siltstone. Sandstone and siltstone make up approximately 60% and 40% of the unit, respectively. The sandstone commonly contains abundant plant detritus, fine-grained amorphous organic matter and small coral(?) fragments. The abundance of terrigenous plant material is suggestive of a relatively near-shore depositional environment. The formation is tightly folded close to the fault but unlike the Temiscouata Formation the cleavage development is relatively poor.

The total thickness of the York Lake Formation in the States Brook map area has not been determined because the lower contact is truncated by the Sainte-Florence Fault and the upper contact is unknown to the west of the map area. Good exposures are located along unnamed logging roads west of the Sainte-Florence Fault in the extreme northwest corner of the States Brook map area (Figure 2c).

The age of the formation is poorly constrained but is estimated to have an Emsian age (Lower Devonian) based on brachiopod fauna (Bourque *et al.* 1995).

Intrusive Rocks

Intrusive rocks in the study area comprise a suite of high-level felsic, and mafic dykes and sills (~0.3–6.0 m thick) that intrude all stratigraphy in the map area. Felsic intrusions are much more common than mafic intrusions and are more likely to be emplaced near major structural features such as the Restigouche–Lower Downs Gulch Fault system. The orientations of the dyke sets tend to vary based on their location. In the States Brook map area, dykes emplaced in the Fortin Group (i.e., Connecticut Valley–Gaspé Synclinorium) are overwhelmingly oriented northwest–southeast. In the Kedgwick, Gounamitz River, and Menneval map areas (i.e., Aroostook–Percé Anticlinorium) the dykes and sills are more randomly oriented and tend to follow both structural and stratigraphic trends. Near the major dextral strike-slip faults (i.e., Restigouche–Lower Downs Gulch faults and the McKenzie Gulch Fault) the dykes are invariably oriented parallel to the faults (north-northeast–south-southwest). The most significant intrusion in the map area is the Patapédia intrusion in the northwest corner of the Menneval map area (Figure 2c). Copper and zinc mineralization are associated with it.

The dykes have inconsistent geophysical expression but are best delineated by the first vertical derivative aeromagnetic response (Kiss *et al.* 2000a–p). Some mafic dykes, such as those in the southern part of the Kedgwick map area, are clearly delineated, whereas those in the eastern part of the Kedgwick map area are not visible by airborne magnetic methods. Similarly, felsic dykes located east of the McKenzie Gulch Fault (Moore and Lentz 1996) are generally clearly delineated, whereas those near and parallel to, the Restigouche Fault commonly have no response. Felsic dykes near the Patapédia intrusion are generally visible on the airborne magnetic maps. Potassium and uranium radiometric maps (Kiss *et al.* 2000a–p) are useful in delineating the alteration associated with larger intrusions, such as at Patapédia.

Felsic Intrusive Rocks

The highest concentrations of felsic rocks are located near and emplaced parallel to, the Restigouche–Lower Downs Gulch Fault system. Other significant swarms are located along, and generally west of, the McKenzie Gulch Fault (Carroll 2000). The felsic rocks vary from greyish green to greyish tan to pinkish orange with brick-red varieties locally. The dykes commonly weather tan-orange to brown, reflecting the presence of Fe-bearing phases such as pyrite and Fe-bearing silicate and carbonate minerals. Most of the dykes are variously feldspar and/or quartz porphyritic with fine-grained to aphanitic groundmasses. Very fine-grained ferromagnesian minerals are observed in some specimens. The dykes range from 30 cm to 3 m in width with "chill" margins evident in the thicker dykes. Host-rock alteration is usually minimal except in the area near the Patapédia intrusion.

The Patapédia intrusion is interpreted to be a high-level granodiorite cupola or stock (Williams-Jones 1982). The main intrusion does not crop out in the study area; however, a broad (about 2.5 km in diameter) contact-metamorphic aureole (Figure 2d) is present surrounding the intrusion and numerous associated dykes/sills crop out within the aureole. The aureole is developed in rocks of the Whites Brook, Pabos, White Head and Temiscouata Formations and oversteps, but is not offset by the Restigouche Fault. In the siliciclastic rocks biotite and calc-silicate hornfels are developed, whereas in the carbonate-bearing rocks andradite–diopside skarn, porcellanite and marbles are developed. The best exposures are located on the Patapédia River, 2 km west if its confluence with the Restigouche River (Figure 2d). Copper and zinc mineralization occurs in the carbonate skarns, although economic quantities of these minerals have yet to be discovered.

Age dating, using the U/Pb zircon method (New Brunswick Geological Surveys Branch, unpublished data, 1999), of a biotite granodiorite dyke within the aureole yielded an age of 364.4 ± 0.4 Ma. This age constrains the latest movement along the Restigouche Fault to the middle Upper Devonian since the aureole is not displaced by the Restigouche Fault.

Figure 17. Medium- to thick-bedded, noncalcareous greyish green sandstone of the York Lake Formation. Note the absence of cleavage. Open compass is 19 cm in length.

Figure 18. Outcrop-scale, upright, shallowly plunging (north-northeast) anticline developed in calcareous sandstone of the Pabos Formation along the Patapédia River.

Mafic Intrusive Rocks

Two mafic intrusive rock suites are recognized in the study area, a diabase suite and a lamprophyre suite. Neither suite is well exposed, although their distribution is, at least in part, indicated by airborne magnetic maps (Kiss *et al.* 2000a–p). Outcrops of these dykes are rare but are most common in eastern part of the Kedgwick map area. The orientations vary from east-northeast to north-northeast and north-northwest. The diabase suite comprises dark green to green, phaneritic, commonly feldspar porphyritic dykes and sills that weather brownish grey to very light grey. The feldspars are in places saussuritized (epidote, sericite, calcite) while the ferromagnesian minerals are locally chloritized. Minor sulphides (pyrite and subordinate pyrrhotite) are typically present.

Two occurrences of lamprophyre are known in the immediate area: one along Grog Brook, 5 km east of Menneval (Figure 2d) and the other along the west side of Highway 17, 500 m south of Five Fingers Brook in the Kedgwick map area (Figure 2a). Elsewhere, lamprophyre (minnette) sills have been documented at Shaws Cove, New Brunswick, 10 km west of Dalhousie and have been studied by Bachinski and Simpson (1984).

The lamprophyre suite comprises brownish green, fine-grained to aphanitic and occellar textured sills that are nowhere observed to be greater than 50 cm thick. The outer margins typically display the occellar texture, whereas the core of the sills are variously fine-grained to weakly porphyritic or aphanitic. The mineralogy consists of small (<1 mm) phenocrysts of phlogopite, clinopyroxene and minor calcic feldspar set in an aphanitic groundmass of brown mica (phlogopite?), feldspar, and possibly pyroxene. Minor olivine is also present.

STRUCTURAL GEOLOGY

Bourque *et al.* (1995), van Staal and de Roo (1995), Malo and Kirkwood (1995) and Malo and Bourque (1993) have investigated the deformational history of the northern Appalachians. They have concluded that there is an early Salinic event that produced minor northwest-trending, open folds and local synsedimentary faulting; followed by a second event associated with the Acadian Orogeny that is manifested by open to locally tight, northeast-trending, doubly plunging folds and concomitant dextral strike-slip faulting. The northwest-trending folds in the study area are attributed to the Salinic uplift and the north-northeast-trending structures to the Acadian orogenic event. In the study area, the movement and associated deformation along the major faults is attributed to the Late Devonian Acadian event.

Folds

Two generations of folds are observed in the study area. The first comprises broad, upright, open to tight, shallowly plunging, northwest-trending folds. They are overprinted by a second generation of tight to locally isoclinal and upright, doubly plunging, north-northeast-trending folds (Figure 18). Two large first-generation structures are observed in the area. The first, in the eastern part of the Kedgwick map area, is a broad, open, west-northwest-plunging anticline that exposes rocks of the Boland Brook Formation (Figure 2a, 2d). The second, in the southwest part of the Kedgwick map area, is a large north- to northwest-trending syncline cored by the White Head Formation (Figure 2a). A cleavage associated with the northwest-trending folds is generally poorly developed, but where observed it is a widely spaced (> 10 cm) fracture cleavage. The broad, open first generation folds are overprinted by tight, upright, north-northeast-trending second generation folds associated with dextral transpression along the McKenzie Gulch Fault (Figure 2a) and the Restigouche–Lower Downs Gulch Fault system (Figures 2b, 2d). A "second" axial-planar cleavage varies widely from moderately developed in the central parts of the Kedgwick and Menneval map areas (Figures 2a, 2d) to very well developed near major faults and is especially well developed in the mudrocks of the Temiscouata Formation.

The overprinting produces typical "dome and basin" or "fish-tail" interference patterns observed in the east and west parts of the Kedgwick map area (Figure 2a). In the northern part of the study area, the fault-associated second deformation is not as intense, even though the same fault systems are present. This is interpreted to be the result of an increase in the compressional component of dextral transpression associated with the flexure (from north-northeast to east-northeast) in the Restigouche and Lower Downs Gulch faults, north of the Patapédia River.

All units in the States Brook and Gounamitz River map areas (Figures 2b, 2c), with the exception of the York Lake Formation, are strongly folded by upright, open to tight north-northeast-trending folds that are attributed to the second deformation event. The fold style and geometry are analogous to that seen in the western part of the Menneval area, described above, but the fold geometries are less chaotic with more consistent plunges (shallow doubly plunging) and larger-scale folding. The dominant structure in the Gounamitz River map area (Figure 2b) is a large second-generation, northeast-trending syncline that is cored by the Gounamitz Lake Formation, which is cut by the Restigouche Fault on its western limb.

Within the study area, the fine-grained carbonate rocks of the White Head Formation and mudrocks of the Temiscouata Formation have absorbed most of the strain as evidenced by the tight to isoclinal, polyclinal folding of the White Head Formation near the major fault zones, and the consistently tight upright folds and well developed cleavage observed throughout the Temiscouata Formation.

Faults

The study area is transected by three major fault zones with complex movement histories that are responsible for the current distribution of the stratigraphy. In the east, the McKenzie Gulch Fault (Figures 1 and 2a) juxtaposes Ordovician Grog Brook siliciclastic rocks of the Aroostook–Percé Anticlinorium against Ordovician–Silurian rocks of the Chaleurs Bay Synclinorium. Large-scale upright, north-trending anticline–syncline pairs and associated faults are developed in rocks of the Boland Brook Formation (Figure 2a). These structures are oriented oblique to, and merge with, the McKenzie Gulch Fault and are consistent with similar structures associated with large dextral strike-slip regimes such as the San Andreas Fault (Christie-Blick and Biddle 1985). The interpretation of dominantly dextral strike-slip motion is consistent with the interpreted movement of other large fault systems in Gaspé and northern New Brunswick including the Rocky Brook–Millstream, Grand Pabos and Restigouche faults (see Figure 1) (van Staal and de Roo 1995; Malo and Kirkwood 1995; and Malo and Bourque 1993). The dextral strike-slip motion was accompanied by high-angle reverse motion as evidenced by the juxtaposition of the older Boland Brook Formation west of the fault against Matapédia Group rocks to the east (Figure 2a). Additionally, Wilson (2002) has documented high-angle reverse motion along the Sellarsville Fault (a related structure) where rocks of the Grog Brook Group are displaced over rocks of the Matapédia Group. Wilson (2002) also proposes earlier synsedimentary normal faulting along the McKenzie Gulch Fault to explain the thickening of Late Silurian strata northwest of the study area.

The Restigouche–Lower Downs Gulch Fault system, the second major zone, juxtaposes rocks of the Connecticut Valley–Gaspé Synclinorium (Fortin Group) against the Aroostook–Percé Anticlinorium (Grog Brook, Matapédia and Perham groups) (Figures 1 and 2b, 2c, 2d). The faults trend northeast to merge with the east-trending Grand Pabos Fault in Gaspé that is estimated by Malo and Bourque (1993) to have 115 km of dextral strike-slip displacement. The extent of strike-slip displacement is not determined in the study area; however, the presence of tightly folded rocks adjacent to the faults suggests that the considerable amount of strike-slip displacement observed in Gaspé was converted to compressive shortening as the orientation of the fault zone changed from east-west in Gaspé to northeast in New Brunswick, and suggests that this flexure was present at the time the fault system was active. Some evidence of high-angle reverse movement is provided

in the Patapédia area (Figure 2d) along the Lower Downs Gulch Fault where thin wedges of Late Ordovician Whites Brook Formation strata are juxtaposed against Lower Silurian White Head Formation rocks.

The Sainte-Florence Fault, the third major fault, is newly recognized in northwestern New Brunswick but is well known in Gaspé. The fault is poorly exposed in the extreme northwest corner of the States Brook map area (Figure 2c) and juxtaposes rocks of the Gaspé Sandstones (York Lake Formation) and Fortin (Temiscouata Formation) groups. Rocks of the calcareous member of the Temiscouata Formation crop out along the south side of this fault and are abruptly replaced by sandstone and siltstone of the York Lake Formation everywhere to the north of this fault. The cleavage is very closely spaced, pervasive and upright in the Temiscouata Formation and poorly developed or absent in the York Lake Formation even thought the latter formation is tightly folded in places. Malo and Bourque (1993) interpret the fault as a northwestward-directed (i.e., northwest-dipping) Acadian thrust. If this is the case, the movement on the fault is relatively limited because the rocks on the hanging-wall (over-thrusted) side are younger than those on the footwall side. The amount of strike slip movement, if any, is not determined.

DISCUSSION AND CONCLUSION

Bourque *et al.* (1995) interpreted the Late Ordovician to Middle Devonian sedimentary record in Gaspé in terms of three regressive events and two transgressive events (Figure 19). The first regressive event (late Caradocian to late Llandoverian) represents basin infilling and uplift following the Middle Ordovician Taconic Orogeny. The second regressive event (late Wenlockian to late Pridolian) followed a Wenlockian sea-level rise and is associated with the Salinic uplift of the Late Silurian. A second transgressive event occurred during the Early Devonian (early Lochkovian to late Pragian) and was followed by the third regressive phase that culminated with the Acadian Orogeny in the Middle to Late Devonian.

In the study area, the transgressive–regressive events of Bourque *et al.* (1995) are mostly absent, with the exception of the Early to Middle Devonian shallowing phase (R3 in Figure 19) that corresponds to the onset of the Acadian Orogeny. This third regression is recognized in the transition from the Temiscouata Formation to the York Lake Formation (Figure 19). The middle Silurian shallowing phase (R1 in Figure 19) is not obvious because the Gounamitz Lake does not contain shallow-water-facies rocks as does Chaleurs Groups in Gaspé. The red shale present in the Gounamitz Lake Formation does not provide convincing evidence of a regressive event because it is interbedded with deep-water graptolite-bearing rocks and the deposition of red shale is not limited to shallow-water environments. The Upsalquitch (at least its upper part) and LaVieille formations (Chaleurs Group in New Brunswick) comprise shallow-water carbonate mudrocks and reef-facies carbonate rocks, respectively, whereas the Spragueville Formation (Perham Group in Maine) comprises shallow-water carbonate mudrocks so that the first shallowing phase (Figure 19) is recognized in these areas (Figure 11, columns 3, 4, 5).

Similarly, the Salinic event is not recognized in the middle Silurian to Devonian stratigraphy in the area, either because it was not significant in this part of the basin or because the stratigraphy recording the uplift has been "cut off" by the Restigouche Fault. The presence of red shale in the Tracey Brook Formation, for reasons mentioned above, is not considered to provide definitive proof of a Salinic regressive phase. In parts of northern New Brunswick, the effect of the Salinic uplift is more pronounced. For example, in the Squaw Cap area (mentioned above), Salinic erosion affected both the Matapédia and Chaleurs groups and resulted in an erosional unconformity above the Chaleurs Group (Figure 11, column 3). Similarly, rocks in the Percé area (Figure 11, column 1) records a Salinic erosional event followed by an Early Devonian transgression and regression. In Maine, the Salinic event is not identified although the deeper-water facies of the Jemtland and

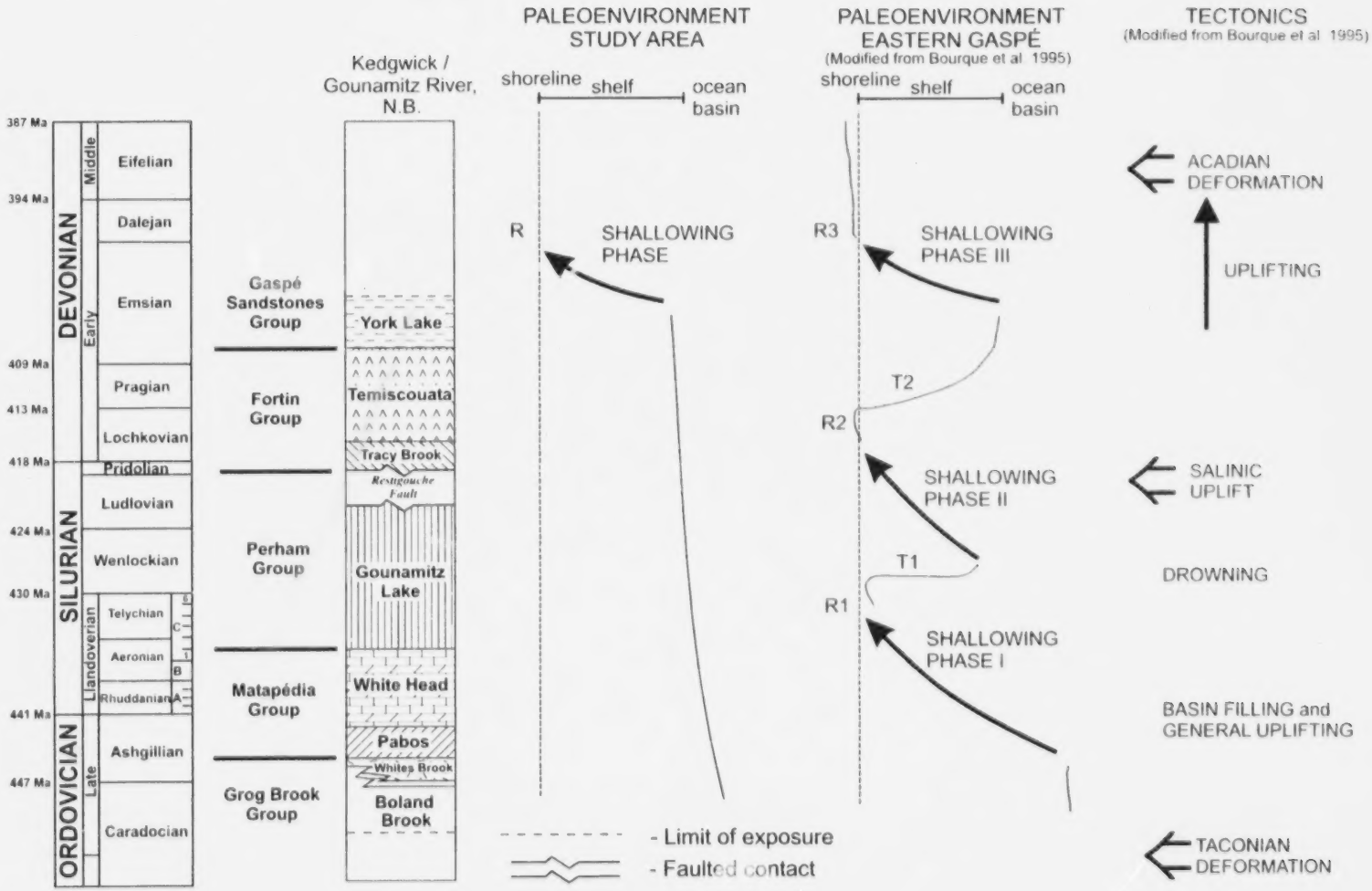

Figure 19. Stratigraphic column of the study area with interpreted regressive–transgressive events in the study area and eastern Gaspé.

Fogelin Hill formations are interpreted by Roy and Mencher (1976) to reflect deepening of the basin in the late Early Silurian; a time corresponding to the deposition of the Tracey Brook Formation and the T1 transgression of Bourque *et al.* (1995) (Figure 19).

The bioturbated, calcareous mudrocks, characteristic of the Spragueville (eastern Maine), Upsalquitch (Squaw Cap area) and Burnt Jam Brook (central Gaspé) formations are lithogically and stratigraphically very similar, suggesting deposition in the same or a connecting series of basins in relatively shallow water. In Maine and New Brunswick, they are mostly confined to the eastern part of the Aroostook–Percé Anticlinorium and Chaleurs Bay Synclinorium, indicating that the emerging terranes were largely confined to the southeast with progressive basin deepening to the west. The northern part of the Gounamitz Lake Formation contains similar bioturbated mudrocks that occur only near the base of the unit at its northern terminus with the Restigouche Fault, suggesting that this part of the basin may have been shallowing (Figure 19, R1) at the time the basal part of the formation was deposited. However, the remainder of the basin was evidently deposited under relatively deep water conditions.

The Gaspé Sandstones Group (York Lake Formation) and the Sainte-Florence Fault are newly recognized in northwestern New Brunswick. The newly recognized *calcareous unit* near the top of the Temiscouata Formation (Figure 2c) indicates some change in the depositional conditions in the basin, perhaps closer to a carbonate bank. The age of the unit (lower Early Devonian) suggests correlation with rocks of the Gaspé Limestones Group (Figure 11, columns 1 and 4); however, current interpretation of the Gaspé stratigraphy (see Bourque *et al.* 1995) indicates that the Gaspé Limestones are wholly replaced by the Fortin Group to the west in the Saint-Jean River Anticline (Figure 11, column 2). Alternatively, the *calcareous unit* may be interpreted as a distal equivalent of the calcareous rocks identified in the base of the York Lake Formation (Gaspé Sandstones Group) in central Gaspé (Bourque *et al.* 1995) that conformably overlies the Gaspé Limestones Group. If sufficient stratigraphy has been removed along the Sainte-Florence Fault the "York Lake Formation" identified north of the Saint-Florence Fault may be equivalent to the siliciclastic rocks of the York River Formation in eastern Gaspé (Figure 14, column 1). However, because the *calcareous unit* is conformable with the underlying Temiscouata Formation in the study area and its upper contact is faulted, the *calcareous unit* is placed in the Fortin Group. The rapid change from the mudrocks of the Temiscouata Formation to thin-bedded argillaceous limestone and siltstone to sandstone with abundant plant detritus in overlying York Lake Formation supports a regression in the late Early Devonian (Figure 19).

The stratigraphic record in the study area interpreted as a record of continuous sedimentation from the Late Ordovician to the Early Devonian punctuated by a single regressive event in the middle Early Devonian. Although an undetermined amount of section is missing along the Restigouche Fault, the depositional similarities between the Gounamitz Lake and Tracey Brook formations and the absence of convincing evidence for intervening shallow-water deposition or an unconformity implies that the basin in the study area was relatively unaffected by the Salinic uplift.

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PROGRESS REPORT: STRUCTURAL INVESTIGATIONS IN THE VICINITY OF THE ROCKY BROOK–MILLSTREAM FAULT, GLOUCESTER AND RESTIGOUCHE COUNTIES, NORTHERN NEW BRUNSWICK †

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Structural investigations in the Sormany quarry, located in the vicinity of the Rocky Brook – Millstream Fault, have shown that the present day thickness of limestone beds in the LaPlante Formation is the result of tectonic thickening by folding. The limestone has been folded into tight, steeply northeast-plunging folds. Minor structures, such as bedding–cleavage intersections and minor bedding-parallel folds, are useful for inferring the direction of plunge of the large folds. The geometry, location, and associated minor structural features of large folds suggest that the folding resulted from regional-scale non-coaxial deformation.

Two systems of faults complicate the structure of the region. The older one has a northeast trend and includes a substantial component of ductile and brittle–ductile deformation (i.e., a shear zone). The younger one has a northwest trend and mostly comprises brittle fractures with the localized occurrence of ductile shearing (i.e., a fault). Numerous shallowly dipping shear planes are interpreted as a product of vertical extension related to strike-slip tectonics. These second-order shears have probably been reactivated as thrust, reverse or normal faults throughout geological time and contribute to the structural complexity of the area.

Des études structurales dans la carrière Sormany, située dans les environs de la faille du ruisseau Rocky–Millstream, ont révélé que l'épaisseur actuelle des bancs calcaires dans la Formation de LaPlante est attribuable à un épaississement tectonique par plissement. Le calcaire a été replié en plis aigus plongeant vers le nord-est. Les petites structures, comme les recoupements de clivage parallèle à la stratification et les petits plis parallèles au litage, sont utiles pour inférer l'orientation de l'inclinaison des plis à grande échelle. La géométrie, l'emplacement et les caractéristiques structurales mineures connexes des plis à grande échelle laissent supposer que le plissement a été provoqué par une déformation non coaxiale à l'échelle régionale.

Deux systèmes de failles compliquent la structure de la région. Le plus ancien est orienté vers le nord-est et il comporte une composante substantielle de déformation ductile et cassante-ductile (c.-à-d. une zone de cisaillement). Le plus récent est orienté vers le nord-ouest et il est principalement constitué de ruptures fragiles avec la présence localisée d'un cisaillement ductile (c.-à-d. une faille). De nombreux plans de cisaillement s'inclinant peu profondément sont interprétés comme un produit d'un prolongement vertical apparenté à une structure tectonique à décrochement horizontal. Ces cisaillements de second ordre ont probablement été réactivés sous forme de failles inverses, chevauchantes ou normales tout au long des temps géologiques et ils contribuent à la complexité structurale du secteur.

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INTRODUCTION

The Rocky Brook–Millstream Fault is a large structure that can be traced from the coast north of Bathurst to the Maine–New Brunswick border, a distance of approximately 225 km (Figure 1). It is a curved structure in which the northeastern part trends easterly and the southwestern part trends northeasterly. The Restigouche–Grand Pabos Fault (in Québec) and Woodstock–Catamaran Fault, to the north and south, respectively, are similar but the major faults in southern New Brunswick lack the easterly trending segment. The study area is situated along the easterly trending segment of the Rocky Brook–Millstream Fault.

In Fyffe and Fricker's (1987) tectonostratigraphic subdivision of New Brunswick, the Rocky Brook–Millstream Fault is interpreted as the northwestern subsurface limit of the highly deformed Miramichi Terrane that is composed of pre-Silurian rocks. Although this fault barely touches rocks of the Miramichi Zone at surface, it transects the Tobique–Chaleur Zone and forms part of the boundary with the Kedgwick Zone (Figure 1). The rocks of the latter two zones and the Edmundston Zone comprise the Late Ordovician to Early Devonian Matapedia Cover Sequence of Fyffe and Fricker (1987). The Matapedia Cover Sequence is equivalent to "Zone 1" of Ruitenberg *et al.* (1977) and constitutes part of the Gaspé Belt of Bourque *et al.* (1995). In fact, the Edmundston, Kedgwick and Tobique–Chaleur zones (Figure 1) are part of Bourque *et al.*'s Connecticut Valley–Gaspé Synclinorium, Aroostook–Percé Anticlinorium, and Chaleurs Bay Synclinorium, respectively.

There is general consensus that the Rocky Brook–Millstream Fault has a dextral strike-slip displacement, but different amounts of offset have been proposed, ranging from 12 km (Fyffe 1982) to 35 km (Bourque *et al.* 1995), up to 60 km (van Staal and de Roo 1995). More detailed structural studies (van Staal and de Roo 1995) also suggest possible reverse (sinistral) reactivation along the fault. However, it should be mentioned that the numbers provided are interpretative. The main evidence for significant dextral displacement along the Rocky Brook–Millstream Fault is based on the compilation map of northern New Brunswick (Davies 1979), which shows apparent horizontal offset of Lower Devonian rocks in a dextral sense. This is not cogent evidence and other interpretations of the separation are possible. However, it is consistent with movement in similar better-exposed shear zones and faults elsewhere in the Appalachians (Park *et al.* 1994). In spite of the wide recognition of strike-slip tectonics in the northern Appalachians, little is known about the actual way in which deformation is accomplished in these fault zones, mainly because of poor exposure. Until now, there has been no detailed structural study devoted to the geometry and mechanics of the Rocky Brook–Millstream Fault.

The research presented in this paper was conducted in and around the Sormany quarry, 28 km to the west of Bathurst, which is at the western end of the Nigadoo River Synclinorium (Davies 1959; Walker *et al.* 1991; Walker *et al.* 1993a, b). The Nigadoo River Synclinorium constitutes that part of the Tobique–Chaleur Zone that is between the Elmtree and Miramichi zones (Figure 1). The quarry is developed in limestone of the LaPlante Formation. It is approximately 800 m long, 150 m wide and is located 500 m to the north of the main trace of the Rocky Brook–Millstream Fault. The distribution of the LaPlante Formation is restricted to the north and south by northeasterly trending faults that are interpreted as subsidiary structures of the main fault (Figure 2). Because of the continuous exposure in the quarry walls, the quarry may be considered a model study area for this very poorly exposed region.

PHYSIOGRAPHY

The permanent and seasonal water drainage in the area accentuate two pronounced trends—one is northeast with a maximum between 030° and 080°, and the other is northwest with a maximum in the range of 310° to 330°. The first system of lineaments is associated with prominent topographic

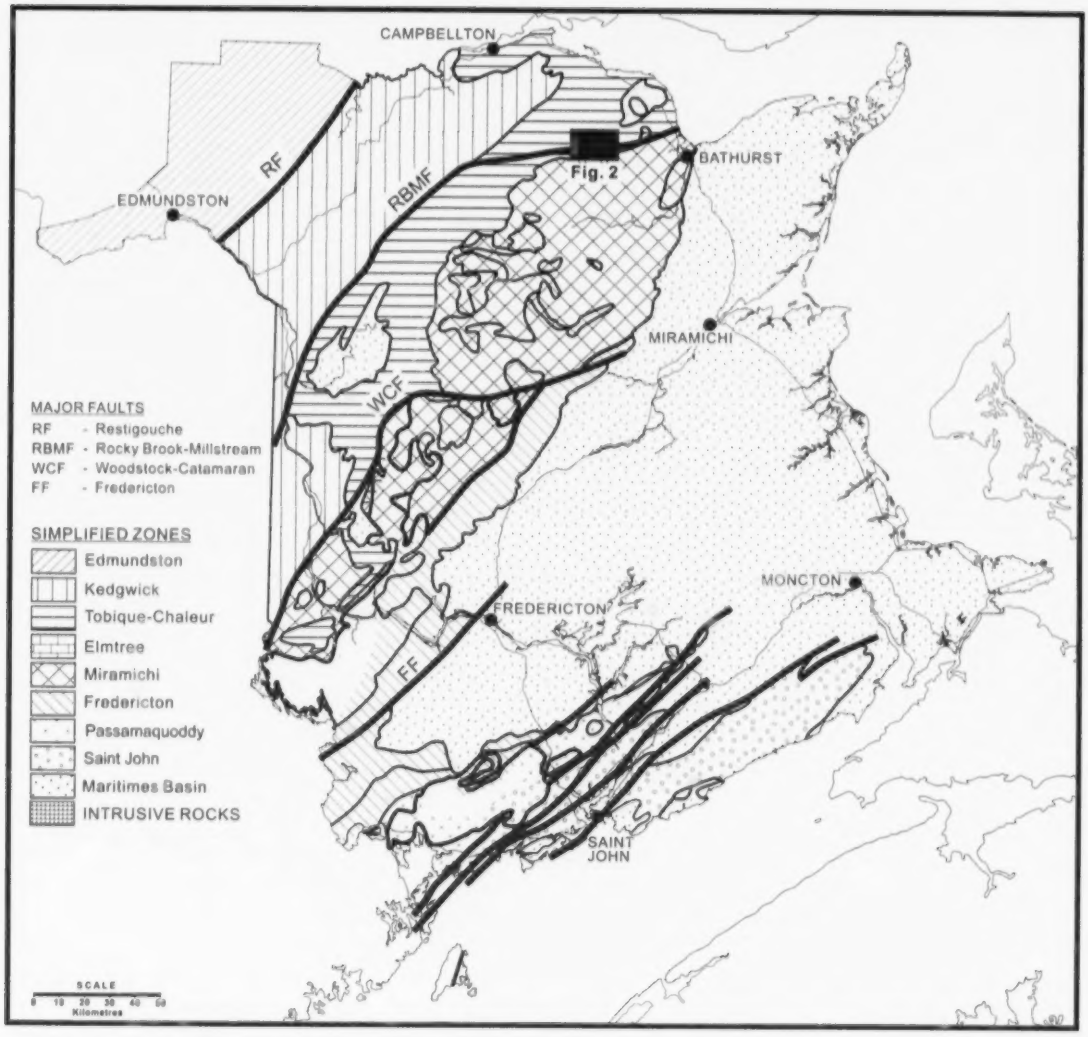

Figure 1. Simplified geological map showing the major faults and metallogenic zones in New Brunswick (modified after Fyffe 2002) and the location of Figure 2.

features that extend over a considerable distance and is accompanied by an array of distinctive physiographic features such as sag ponds, deflected river valleys or dry valleys. The second system of lineaments, which is parallel to a common fault direction, trends to the northwest and has a less pronounced effect on topography. Nonetheless, these lineaments are clearly recognizable and more closely spaced than the first group. The less pronounced topographic expression of the northwestern system may reflect the direction of glacial transport, which is from west to east. The negative landforms that are at a high angle to the direction of glacial flow tend to be filled with sediments. This study and another by Williams *et al.* (1995) show that northwest-trending faults are generally younger than the northeast-trending set.

STRATIGRAPHY

The Silurian Chaleurs Group has been subdivided into ten formations, in ascending stratigraphic order, namely: Clemville, Weir (formerly Armstrong Brook), Upsalquitch, La Vieille, Simpsons Field,

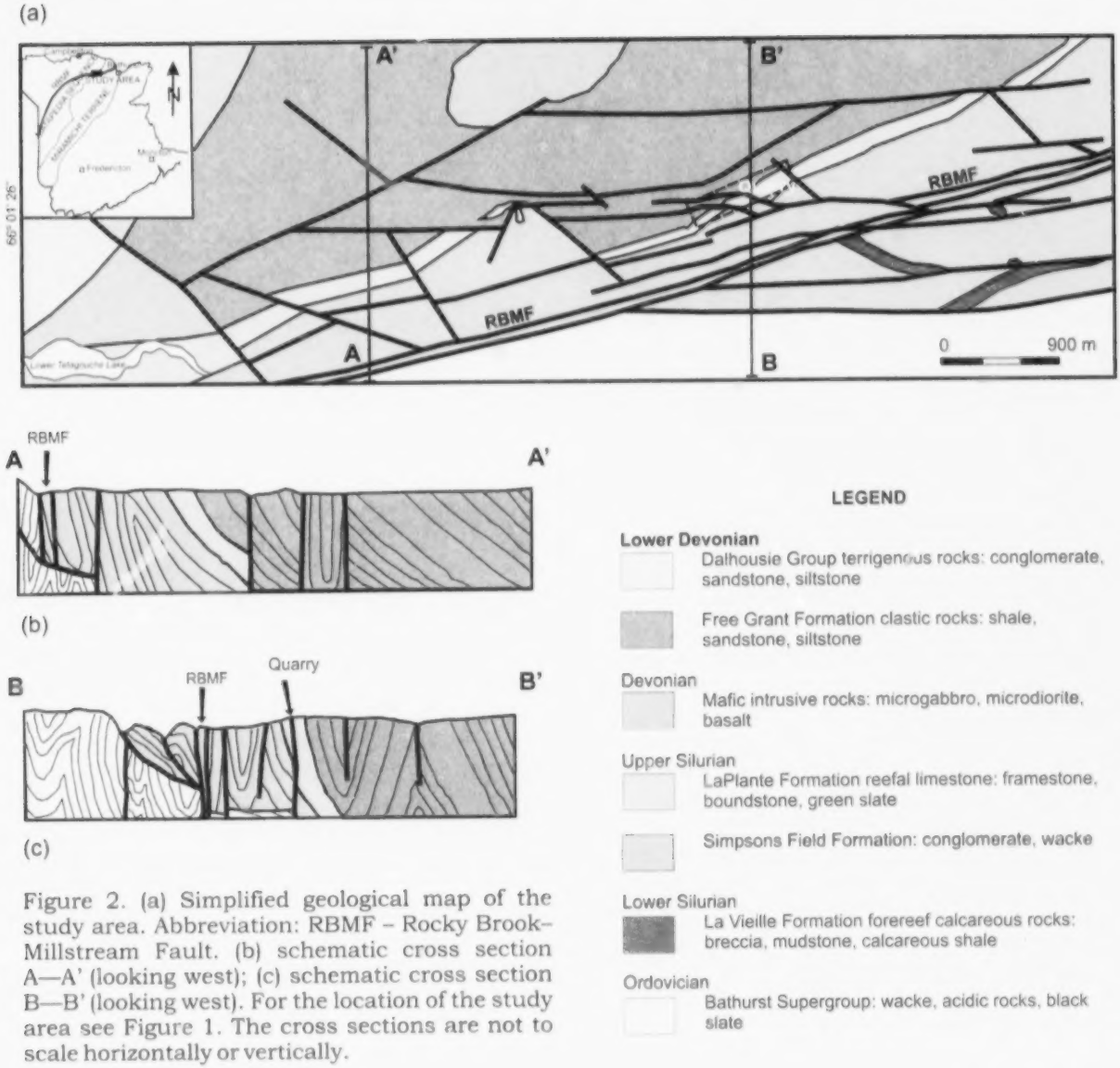

Figure 2. (a) Simplified geological map of the study area. Abbreviation: RBMF – Rocky Brook–Millstream Fault. (b) schematic cross section A—A' (looking west); (c) schematic cross section B—B' (looking west). For the location of the study area see Figure 1. The cross sections are not to scale horizontally or vertically.

South Charlo, Bryant Point, Benjamin, LaPlante and Free Grant (Walker *et al.* 1991; Walker *et al.* 1993a, b). In the study area, only four of these formations are present, namely: La Vielle, Simpsons Field, LaPlante and Free Grant (in ascending stratigraphic order). During this detailed structural study of the deformation style in the Sormany quarry area, rocks of the LaPlante Formation and, to a limited extent, the Simpson Field Formation were examined.

The Simpsons Field Formation is composed of coarse-grained, terrigenous rocks that occur both north and south of the Rocky Brook–Millstream Fault. In the north, it comprises a coarsening-upward unit that is capped by basalt-clast conglomerate with a strong magnetic signature. The clasts were derived from Ordovician basalts exposed south and west of the Sormany quarry. This conglomerate is cut by the Nicolas Denys Granodiorite (381 ± 4 Ma, U–Pb, Walker *et al.* 1993a), the contact aureole of which is offset approximately 1 km by the Rocky Brook–Millstream Fault. To the south of this Fault and east of the quarry, the Simpsons Field Formation does not contain this

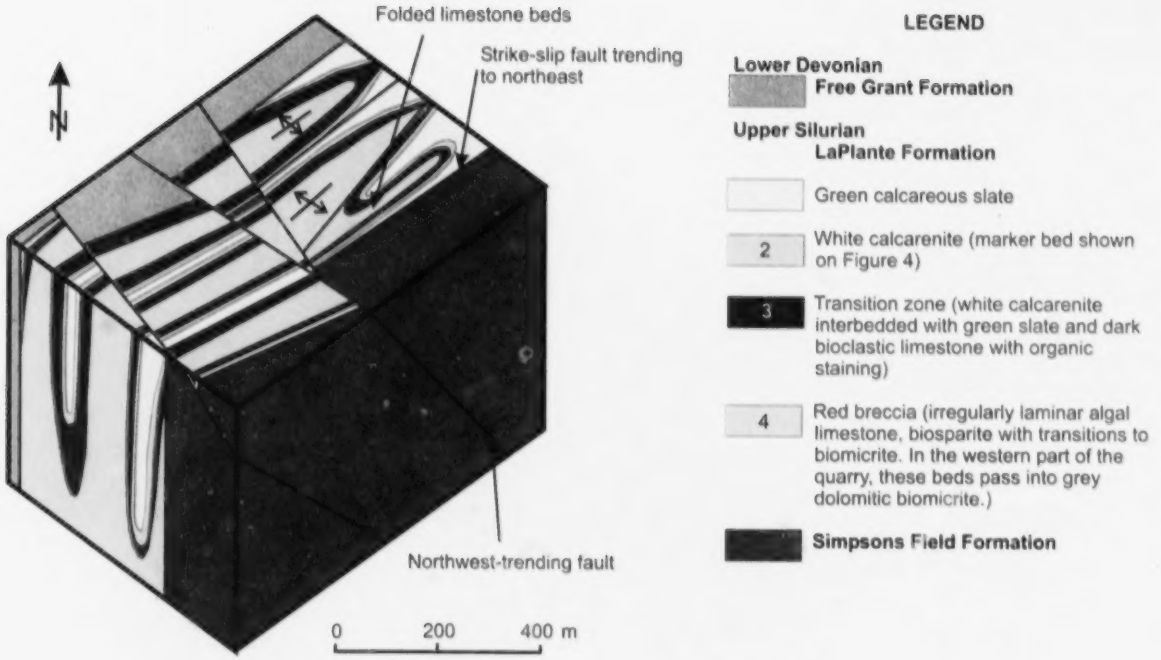
Folded limestone beds
Strike-slip fault trending to northeast
N
Northwest-trending fault
0
200
400 m
LEGEND
Lower Devonian
Free Grant Formation
Upper Silurian
LaPlante Formation
Green calcareous slate
2
White calcarenite (marker bed shown on Figure 4)
3
Transition zone (white calcarenite interbedded with green slate and dark bioclastic limestone with organic staining)
4
Red breccia (irregularly laminar algal limestone, biosparite with transitions to biomicrite. In the western part of the quarry, these beds pass into grey dolomitic biomicrite.)
Simpsons Field Formation

Figure 3. Block diagram illustrating the structures observed in the Sormany quarry. The upper face represents the surface geology. See Figure 2 for location.

conglomerate and it fines upward rather than coarsens upward. This indicates that the western part of the Miramichi Terrane was exposed and providing erosional detritus to the Simpsons Field, whereas the eastern side was not. Furthermore, it implies that the Rocky Brook–Millstream Fault may have existed at the time the conglomerate was being deposited, which was first suggested by Walker *et al.* (1993a).

The Simpsons Field Formation is overlain by calcareous rocks of the LaPlante Formation and underlain by limestone of the La Vielle Formation. South of the Rocky Brook–Millstream Fault, the LaPlante Formation is absent and the La Vieille Formation is not well preserved. For the most part, the LaPlante Formation comprises calcareous shales, but locally contains allochthonous accumulations of limestone. Noble (1985) concluded that limestones of the Pridolian LaPlante Formation were derived by resedimentation of small reefs, built mainly by laminar stromatoporoids and stromatolitic algae and, consequently, comprise mudstones and extensive biogenic and polymictic breccias. The fauna of the reefal limestone suggests a rather low-energy environment and the associated internal breccia and mudflows suggest that the reef mounds were deposited on the upper slope at the margin of a narrow shelf. Because of the tectonic transport and structural stacking of originally remote carbonate facies (Figure 3), detailed structural studies are required before paleogeographic reconstruction is attempted.

The Free Grant Formation conformably overlies the LaPlante Formation. It comprises interbedded, weakly calcareous sandstone and greenish grey siltstone. It occupies the core of the Nigadoo River Synclinorium (Walker *et al.* 1993a, b).

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Figure 4. Large folds in the Sormany quarry. The photograph was taken from the middle of the quarry looking northeast. The high wall in the middle of the picture is approximately 12 m high. Numeration of the beds is the same as in Figure 3.

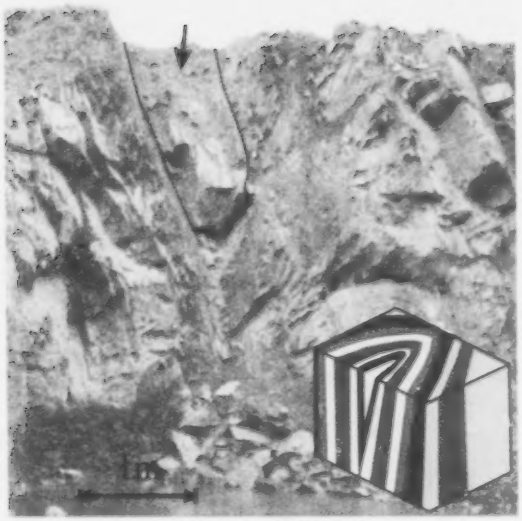

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Figure 5. Core of a large fold exposed in the quarry. The fold hinge plunges steeply northeast. Small folds (too small to be seen in the photograph) plunge in the same direction as the hinge of the large fold.

STRUCTURE

Basin control and age constraints on deformation

Stratigraphic evidence suggests that deposition of the Chaleurs Group in this region was controlled by a precursor of the present Rocky Brook–Millstream Fault, located near the contact with the Ordovician terrane to the south. At the time of deposition of the Simpsons Field Formation, the Ordovician terrane was rising, resulting in deposition of a coarsening-upward sequence that culminated in deposition of conglomerate north of the Rocky Brook–Millstream Fault. The Ordovician terrane supplied basalt clasts, which is the reason for the strong magnetic signature of the conglomerate (Walker *et al.* 1993a). This conglomerate is absent in stratigraphically equivalent rocks east of the quarry, but it occurs west of the quarry where it unconformably overlies Ordovician rocks. In addition to the conglomerate, a string of reefs developed (LaPlante Formation) along the boundary of the basin. Tectonic instability along the precursor fault is said to have resulted in redeposition of reefal material of the LaPlante Formation in the basin (Noble 1985), which bears the marks of gravitational sliding, as described by Cook and Mullins (1983).

Ductile deformation in the Rocky Brook–Millstream Fault zone

The LaPlante limestone in the quarry is almost completely recrystallized, comprising a framework of biogenic carbonate detritus, cemented by abundant sparry calcite. It has undergone ductile deformation under cold conditions. The coarse grains are now lenticular. Because of the lack of rheological contrast between the fragments and the matrix, it is difficult to find typical shear-sense indicators, in spite of the intense shear. The structures observed have been subdivided into ductile and brittle types. Some structures may be brittle in shale but ductile in limestone. For this reason, the brittle–ductile subdivision is conditional and dependent on the different rheological properties of the limestone and the clastic rocks that enclose it. The limestone tends to be deformed by mechanical twinning and solution transfer; it behaves in a ductile manner even though the enclosing rocks deform in a more brittle manner.

Folds: The distribution of a bed of sugar-white, coarse-grained limestone at the top of the carbonate unit (Figure 4) shows that the LaPlante Formation has been folded into large tight folds (Figures 3, 4, and 5). Wherever there are large and small folds together, the hinges are parallel. The small folds plunge in opposite directions, varying from near horizontal to near vertical, implying similar plunges for the large folds. Plunges are consistently to the northeast and southwest (Figure 6). The limbs and the axial planes of the folds strike between 035° and 045°, whereas the strike of the lineaments of the Rocky Brook–Millstream Fault zone vary between 060° and 080°. Small, second-order folds are not common in the limestone but they are abundant in green slate, which is interbedded with limestone near the top of the LaPlante Formation and in the overlying Free Grant Formation. Structural analysis of the bedding in the green slate as well as observations in several small exposures indicate that the minor folds in the slate have a shallow plunge to the northeast (Figure 7).

Bedding–cleavage relationships: Subvertical penetrative cleavage strikes 030° to 045°. The cleavage–bedding intersection defines a lineation that plunges parallel to the hinges of the folds. Bedding is locally recognizable in the limestone because of slate interbeds but the fine-scale layering is parallel to cleavage and probably of tectonic origin.

Lineation: On faces parallel to bedding, the lineation is defined by hinges of small folds (Figure 8). The lineation shows the orientation of the major fold hinges. The wavelength of the small folds varies from several millimetres to 0.5 m. The small folds are best manifested in the contact surfaces between thin, shaly beds that are intercalated with the limestone.

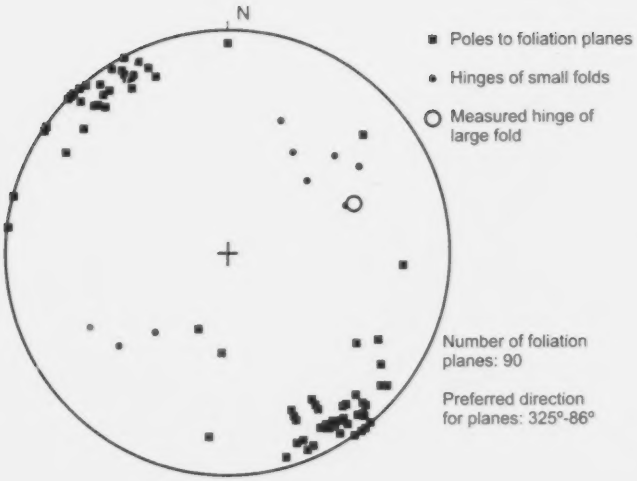
N
Poles to foliation planes
Hinges of small folds
Measured hinge of large fold
Number of foliation planes: 90
Preferred direction for planes: 325°-86°

Figure 6. Equal-area projection (lower hemisphere) showing foliation planes in the limestone of the Sormany quarry. The hinge of the fold from Figure 5 is indicated as "measured" on the projection.

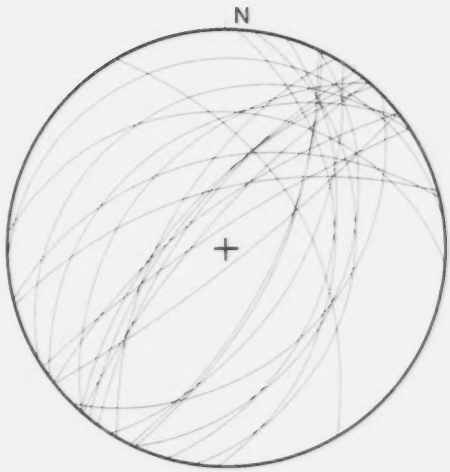

Figure 7. Equal-area projection (lower hemisphere) showing bedding planes in the upper part of the LaPlante Formation. The orientation of the beds was found by assembling apparent dips in the eastern part of the quarry. The number of measured planes is 24.

The orientation of the hinges of the small folds corresponds to the measured orientation of the hinges of the large folds and to the statistically derived intersections of the bedding planes (Figures 6 and 7). Direct observations of the closures of several large folds (Figure 5) confirm this. The hinges of the small folds, which can be traced for tens of metres, are consistently parallel to the hinges of the large folds. Consequently, the small folds are useful for recognizing the direction of fold plunge in domains where the fold geometry is not directly measurable.

The conglomerate clasts of the Simpsons Field Formation, south of the LaPlante Formation, do not show an obvious stretching lineation. The clasts represent a variety of rock types but basalt, wacke, acid volcanic rocks, and chert predominate. They are strongly flattened in the cleavage plane but they have no preferred orientation. Measurements from the conglomerate are erratic and have not been utilized in the preparation of the proposed tectonic model.

Ductile shear zones: A variety of shear zones have been identified in the quarry, ranging from arrays of tension gashes to major, shallow-dipping shear surfaces with reverse and normal sense of displacement. One particular type of shear zone, which is characteristic of the LaPlante Formation, is manifested by zones of tension gashes and solution transfer seams in shale beds (Figure 9). Some of the shear zones are simply semiductile analogs of the northwest-trending faults. These zones change their degree of ductility according to the rocks they transect.

In limestone, the shear zones are ductile and manifested by small folds plunging in opposite directions (Figure 10). In a sense, this style of shear-related folding is a small-scale analogy of the large-scale folding in the quarry. As in the macro-scale system, the folds plunge in opposite directions, and the axial planes are sheared roughly parallel to the shear zone boundaries. A bedding-parallel lineation is parallel to the fold hinges. However, where the shear zone crosses shale beds, it has the characteristics of a brittle fault.

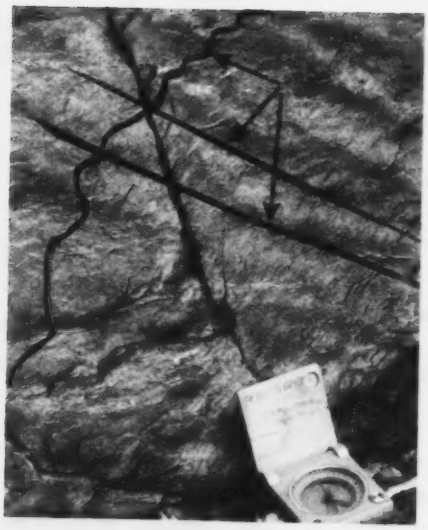

Figure 8. Small-scale folds on the southeast wall of the quarry. The wavy line emphasizes the troughs and crests of synforms and antiforms on the bedding surface. Straight lines indicate the orientation of the fold hinges that plunge to the southwest. The compass is 10 cm across.

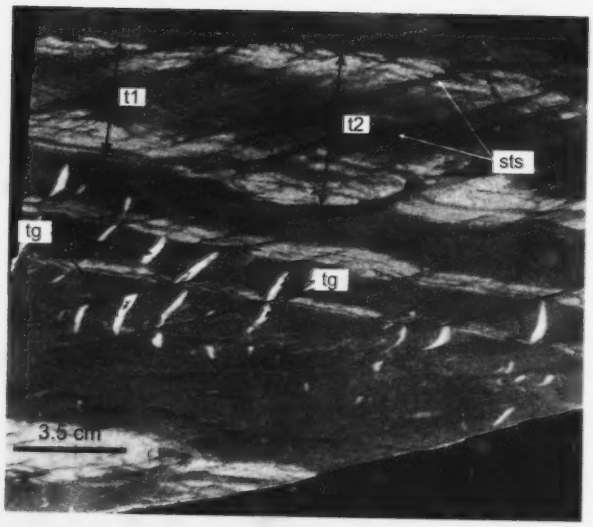

Figure 9. Sample (colour exaggerated to bring out texture) from a small shear zone in the green slate of the LaPlante Formation located in the northeastern part of the quarry. Transport of material related to the solution transfer seams (sts), changed the thickness of a marker white siltstone bed from t1 to t2. Calcite-filled tension gashes (tg) are seen in arrays parallel to the solution transfer seams.

Drag folds: Late northwesterly striking faults cut and displace the folded LaPlante Formation, and either exhibit normal extensional movement or strike-slip movement. These faults exhibit well-developed fault-drag folds (Figure 11). Since the faults are closely spaced, the folds are ubiquitous. The axial plane orientation and the localization of the fault-drag folds are controlled by two big northwest-striking faults that displace the limestone beds in the quarry. The folds are generally small scale, commonly sheared along the axial planes, and are acute-angled structures.

Brittle deformation associated with the Rocky Brook–Millstream Fault zone

Faults: Faults with predominant strike-slip movement cut limestone and shale of the LaPlante Formation and transport them to the northwest or southeast. The fault zones are 1–3 m wide and the greatest horizontal offset of the limestone is compatible with approximately 800 m in a dextral sense (Figure 2). As a result, a wide gap was created to the west of the quarry, where the LaPlante Formation is missing. A gradual increase of rock fragmentation is observed from the margins towards the middle of the fault zones. The high-strain domains, as indicated by the degree of brecciation, comprise a chaotic mixture of randomly oriented blocks cemented by fault gouge in the middle of the fault zones. In low-strain domains, in the margins of the fault zones, ductile conjugated shears and fractures are observed together with drag folds, which show the sense of shear. A large number of small faults have been observed in the quarry (Figure 12). Direct measurements of the orientations of the fault planes and the lineations in them are possible only for relatively minor secondary faults or splays of the big faults, which are away from the zones of intense brecciation. Because of this, the surfaces that allow measurement rarely coincide in orientation with the major fault. On some of the small faults, the presence of two or three directions of slickenside lineation or grooves suggests that these lineations are not reliable indicators for the displacement direction along the major faults. Intensive jointing is observed in

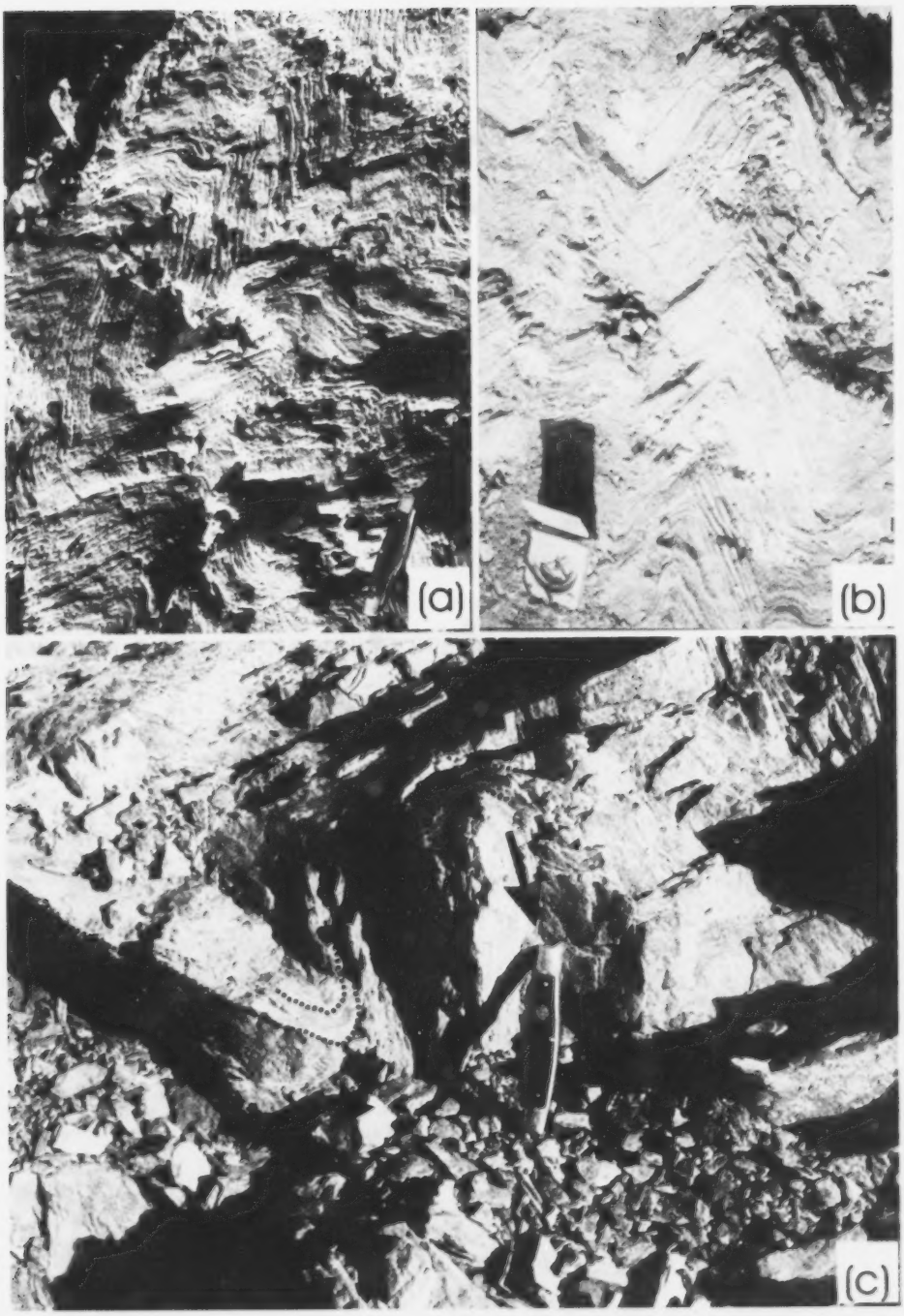

Figure 10. Plan view of vertically dipping, ductile shear zone (striking 320°) in the northwestern part of the quarry showing intense folding of the limestone beds; viewed looking (a) northwest, (b) southeast, and (c) obliquely north showing folds plunging in opposite directions. The pocket knife in (a) and (c) is 9 cm in length. The compass in (b) is 10 cm across.

the quarry (Figure 13), which makes distinguishing major joints from small faults difficult.

A conjugate system of normal faults has been observed. The extensional faults commonly reflect a pattern of "domino"-type rotation (Nur *et al.* 1986) above a common detachment surface. Several detachment surfaces have been documented that dip at less than 45° (Figure 14). Some of the subhorizontal fault planes locally pass into ductile shear zones. The ductility is manifested by cataclastic flow, which tends to round the rock fragments, and mechanically re-orient them so that a lenticular fabric is created that resembles a discontinuous foliation.

Joints: Two distinct joint sets in the quarry strike to the northwest approximately normal to the strike of the limestone body, but dip to the northeast and southwest (Figure 14). The spacing between the individual joints varies between 0.1 and 0.3 m. They are conjugate and interpreted as being genetically related to the faults of the extensional system.

CONCLUSIONS

The large folds observed in the quarry are attributed to transpression that initiated movement along the Rocky Brook–Millstream Fault (cf. van Staal and de Roo 1995). It is likely that the boundary conditions involved during folding were analogous to those in the model described by Williams *et al.* (1995), i.e., the folds are shear-related. The evidence in support of this is as follows:

1. The axial planes of the folds are faulted and oblique to the direction of the lineaments of the Rocky Brook–Millstream Fault (see Figure 10).

2. As predicted by the model, the adjacent folds plunge steeply and in opposite directions. The deformational events that followed the folding were brittle and the structures related to them more or less utilized the discontinuities formed during the transpression.

From this work and review of the previous research (Davies 1959; Walker *et al.* 1993a; Williams *et al.* 1995; van Staal and de Roo 1995), we may conclude that the complex structure in the study area evolved during two major events:

1. Transpressional folding and faulting generally attributed to the Acadian deformation.

2. Faulting locally coupled with folding and rigid-body rotation that may be related to subsequent extension of the Appalachian Orogen.

ACKNOWLEDGMENTS

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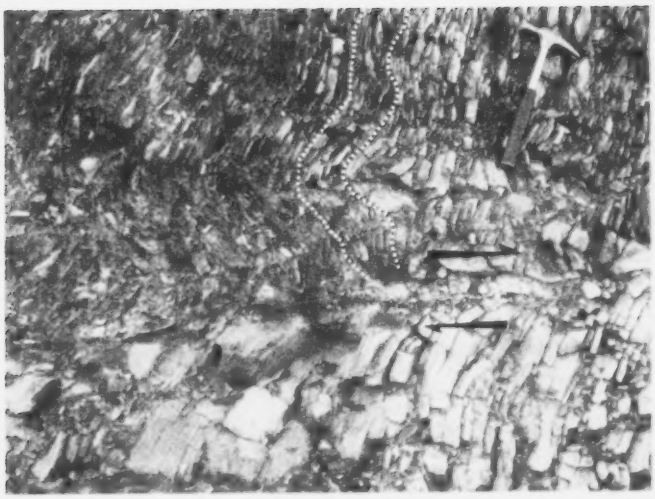

Figure 11. Fault-drag folds adjacent to fault trace. The arrows indicate the sense of shear along the fault. Vertical face viewed looking west. Dotted line represents the trace of bedding. Hammer is 35 cm long.

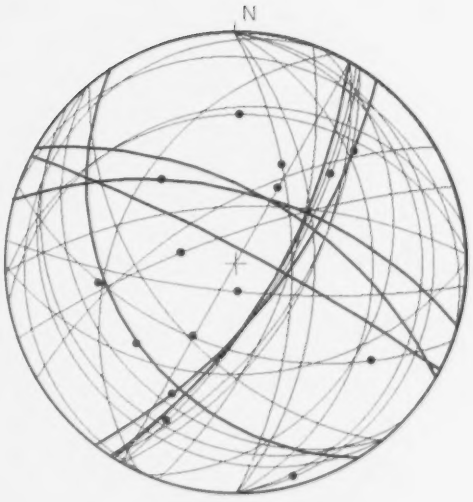

Figure 12. Equal-area projection of faults (n = 34) measured at 20 different localities in the quarry. Larger faults are shown with thick lines. Directions of grooves measured in some of the fault planes are shown as black dots.

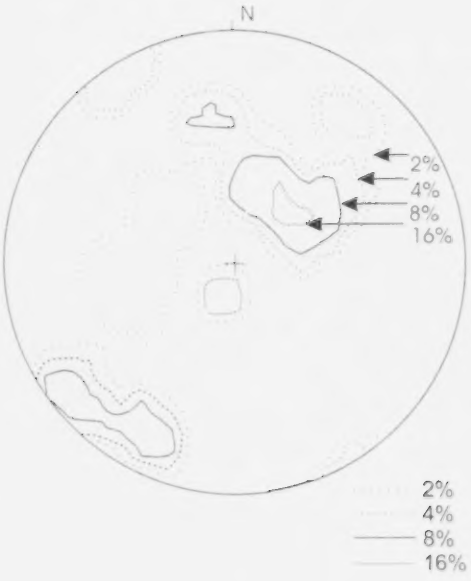

Figure 13. Equal-area projection, lower hemisphere, showing the statistical distribution of joints (n = 60) measured throughout the quarry. The densities of the contours are expressed in units of % per 1% area.

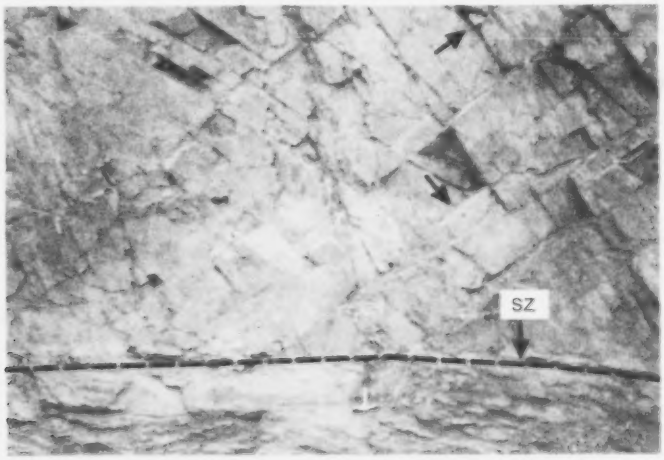

Figure 14. Low-angle, ductile shear zone indicated by the dotted line. Two conjugate joint sets above the shear plane are indicated by arrows. Vertical face looking northwest. Hammer is 35 cm long.

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THE A'HEARN BROOK Zn–Pb–Cu–Ag MASSIVE SULPHIDE DEPOSIT (NTS 21 O/08 EAST), BATHURST MINING CAMP, NEW BRUNSWICK †

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The A'Hearn Brook deposit is a small (< 70 000 t), high grade (best assay 32.5% Zn, 22.7 wt. % Pb and 1.6 wt. % Cu) sulphide deposit occurring within an intercalated sequence of felsic volcanic and fine-grained clastic sedimentary rocks of the Flat Landing Brook Formation.

The host rocks are feldspar phyric lavas, ash and crystal tuffs, and minor intercalated sedimentary rocks. Locally, aphyric to sparsely feldspar-phyric rhyolite is interlayered with the crystal-rich rocks. Most felsic volcanic rocks are transitional between dacitic and rhyolitic compositions. However, three are andesitic and, possibly, part of the Moody Brook Member of the Flat Landing Brook Formation.

The sulphide lens is overlain and locally immediately underlain by a sequence of red manganiferous shale and chert that is assigned to the Roger Brook Member (Flat Landing Brook Formation). The cherts and shales are probably dominantly hydrogenous precipitates as they have relatively low Fe/Mn ratios (< 4), and have positive Ce anomalies ($Ce/Ce^* > 1$). Notably, these rocks have elevated W, Sb, As, Ag, and Au relative to other host rocks. Similar rocks are spatially related to volcanogenic massive sulphide style of mineralization at the Strachens Lake deposit (3 km to the southwest).

The A'Hearn Brook sulphide body probably formed as a stratiform volcanogenic massive sulphide deposit in a third order anoxic basin into which volcanic ejecta/debris was being deposited. The absence of Cu-rich stringer mineralization and footwall chlorite-altered rocks implies that the deposit formed in a setting distal to the vent complex.

Subsequent deformation remobilized the sulphide lens into its present configuration. The remobilization and/or recrystallization is responsible for atypical sulphide textures (e.g., rounded pyrite in a sphalerite matrix) and local very high grade.

Le gîte du ruisseau A'Hearn constitue un petit (< 70 000 t) gîte de sulfures à forte teneur (meilleur titrage : 32,5 % de Zn, 22,7 % pds de Pb et 1,6 % pds de Cu) se trouvant à l'intérieur d'une séquence intercalée de roches sédimentaires clastiques à grain fin et de roches volcanofelsiques de la Formation de Flat Landing Brook.

Les roches hôtes comprennent des laves porphyrofeldspathiques, des cendres et des tufs cristallins ainsi qu'une petite quantité de roches sédimentaires intercalées. De la rhyolite aphyrique devenant porphyrofeldspathique de façon clairsemée est localement interstratifiée de roches riches en cristaux. La majorité des roches volcanofelsiques présentent des compositions marquant une transition entre des teneurs dacitiques et rhyolitiques. Trois unités sont toutefois andésitiques et font possiblement partie du membre du ruisseau Moody de la Formation de Flat Landing Brook.

La lentille de sulfures est recouverte par une séquence de cherts et de schistes manganifères rouges rattachée au membre du ruisseau Roger (Formation de Flat Landing Brook) et elle repose par endroits immédiatement sur cette séquence. Les cherts et les schistes constituent probablement des précipités en prédominance hydrogènes, car ils présentent des ratios de

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† New Brunswick Geological Surveys Branch ordinary budget.

Fe/Mn relativement bas (< 4) et des anomalies positives de Ce (Ce/Ce* > 1). Ces roches possèdent notamment des teneurs élevées en W, Sb, As, Ag et Au comparativement aux autres roches hôtes. Des roches semblables sont spatialement apparentées à un type de minéralisation à base de sulfures massifs d'origine volcanique dans le gîte du lac Strachens (trois kilomètres au sud-ouest).

La masse de sulfures du ruisseau A'Hearn s'est probablement formée sous l'aspect d'un gîte volcanogène et stratiforme de sulfures massifs dans un bassin anoxique de troisième ordre à l'intérieur duquel des éjecta/débris volcaniques ont été déposés. L'absence de minéralisation à filonnets riche en Cu et de roches chloritisées de lèvre inférieure signifie que le gîte s'est formé dans un cadre distal du complexe de la cheminée volcanique.

Une déformation subséquente a remobilisé la lentille de sulfures dans sa configuration actuelle. La remobilisation ou recristallisation explique les textures atypiques des sulfures (p. ex. pyrite arrondie dans une gangue de sphalérite) et la teneur extrêmement élevée par endroits.

INTRODUCTION

The A'Hearn Brook project was undertaken in order to determine the stratigraphic position of mineralization with respect to the regional stratigraphic framework, and to document the styles of mineralization and hydrothermal alteration. The A'Hearn Brook deposit (also spelled O'Hearn in older literature), New Brunswick Department of Natural Resources unique record number (URN) 0120, is located in the central part of the Bathurst Mining Camp, approximately 45 km southwest of the city of Bathurst, and 3.75 km northwest of California Lake (Figures 1 and 2). The geology in this part of the Camp is particularly complex and interpretation is hampered by numerous high-strain zones and the absence of outcrop in key areas (Figure 2). The paucity of outcrop in the immediate vicinity of the deposit necessitated the extensive use of samples collected from trenches and drill core (courtesy of Slam Exploration Ltd.), and of data compiled from mineral assessment reports of work.

PREVIOUS WORK

Early exploration in this area was conducted by New Jersey Zinc Exploration Company (Canada) Ltd. (Benson 1959), Dome Exploration (Canada) Ltd. (Moreau 1961), Mount Costigan Mines Ltd. (Tellford 1965; Newell 1965) and Selco Exploration Company Ltd. (Geisler 1955). In 1968, the A'Hearn Brook–Strachens Lake area was taken over by the Findathoran Syndicate (Power 1969). Findathoran's exploration included geological mapping, soil geochemistry, and induced polarization surveys, as well as diamond drilling (9 diamond-drill holes; OH-5 through OH-12). In 1970, Findathoran continued exploration with an induced polarization survey, soil sampling, and 1250 m of AX and BX diamond drilling (drill holes OH-13 through -18, OH-46 through -51, OH-58 through -60), which ultimately led to the discovery of sulphide mineralization at A'Hearn Brook (Power 1970). In 1973, additional diamond drilling of 25 holes (OH-19 through -21, OH-31 through -45, OH-52 through -57, and OH-61) was focused on testing the limits of the sulphide lens (Power 1982).

In 1980, the property was taken over by Noranda Exploration Company Ltd., which carried out line cutting, geological mapping, soil geochemistry, magnetic, gravity, horizontal-loop electromagnetic and induced polarization surveys as well as diamond drilling of five holes (MacKenzie 1981a, 1981b, 1982). From 1983 to 1984, a very low frequency survey was carried out and eight holes were drilled (MacKenzie 1982, 1983; Kempster 1990, 1991). Subsequent work included collection of 47 pionjar samples (Csabai 1992), lithogeochemical sampling of previously drilled core (Kempster 1993), and trenching (Frotten 1994). A deep drill hole collared north of the surface trace of the

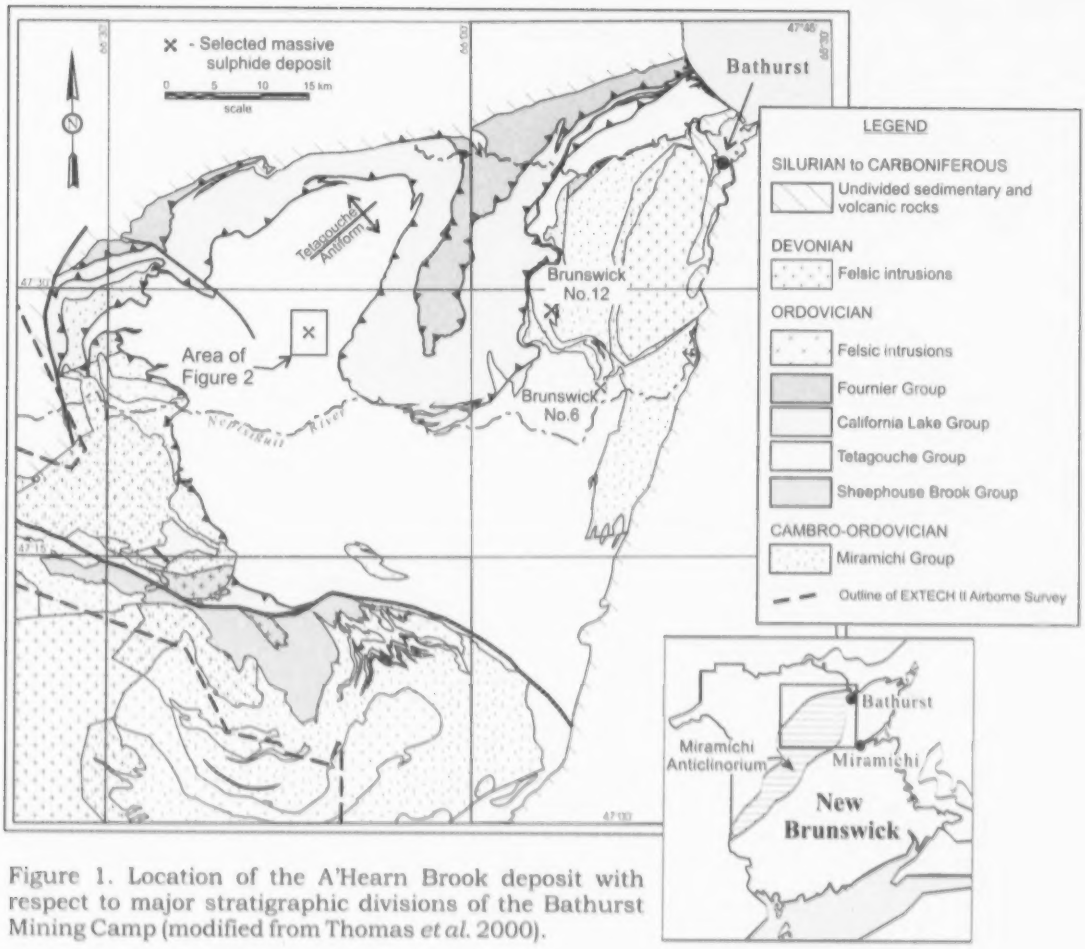


Figure 1. Location of the A'Hearn Brook deposit with respect to major stratigraphic divisions of the Bathurst Mining Camp (modified from Thomas *et al.* 2000).

sulphide lens was drilled to a depth of 544 m (Beaumont-Smith 1995), and was successful in intersecting two mineralized horizons, although the base-metal grades were very low.

Most recently Slam Exploration Ltd. carried out a trenching and shallow diamond-drilling program (drill holes OH-02-01 through OH-02–06) on the property (Brown 2002). The position of drill-hole collars and trench locations from which data were compiled are located on Figure 3.

REGIONAL GEOLOGY

The Bathurst Mining Camp comprises a polydeformed Middle Ordovician sequence of bimodal volcanic and intercalated sedimentary rocks deposited in a back-arc basin that formed on Cambro-Ordovician siliciclastic rocks (flysch sequence) bordering a stable peri-Gondwanan continental margin (van Staal and Fyffe 1991).

The Bathurst Mining Camp contained a pre-mining geologic resource of 349 000 000 t of massive sulphide (McCutcheon *et al.*, in press). Since the discovery of the Brunswick No. 6 ore body in 1952 (Belland 1992), the camp has produced more than 134 000 000 t of ore grading 3.05% Pb, 7.82% Zn, 0.46% Cu and 91.5 g/t Ag (McCutcheon *et al.*, in press). There are 46 known volcanogenic massive sulphide deposits in the Bathurst Mining Camp and all are spatially associated with felsic

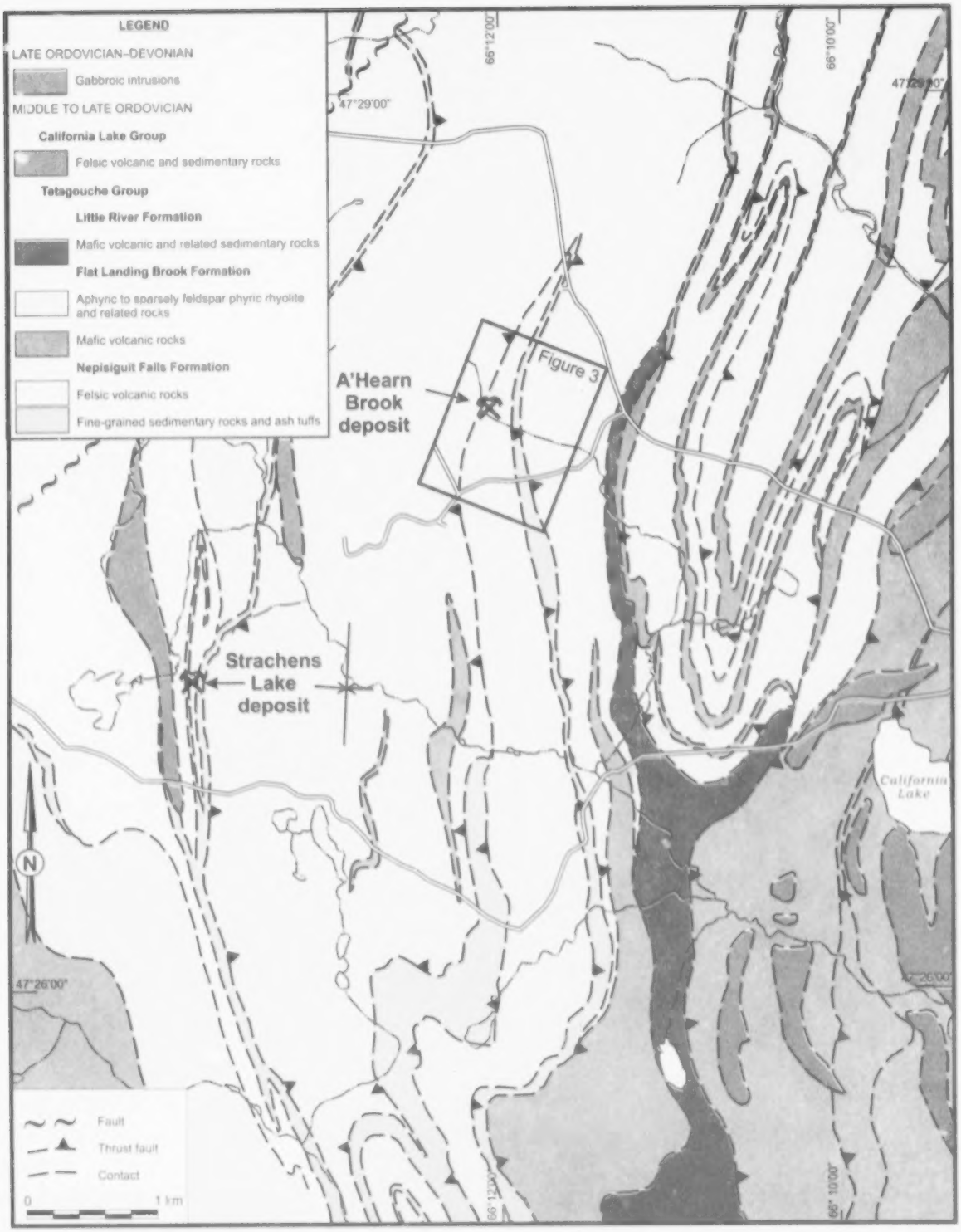


Figure 2. Regional geology in the vicinity of the A'Hearn Brook deposit. Simplified from van Staal *et al.* (2002). See Figure 1 for location.

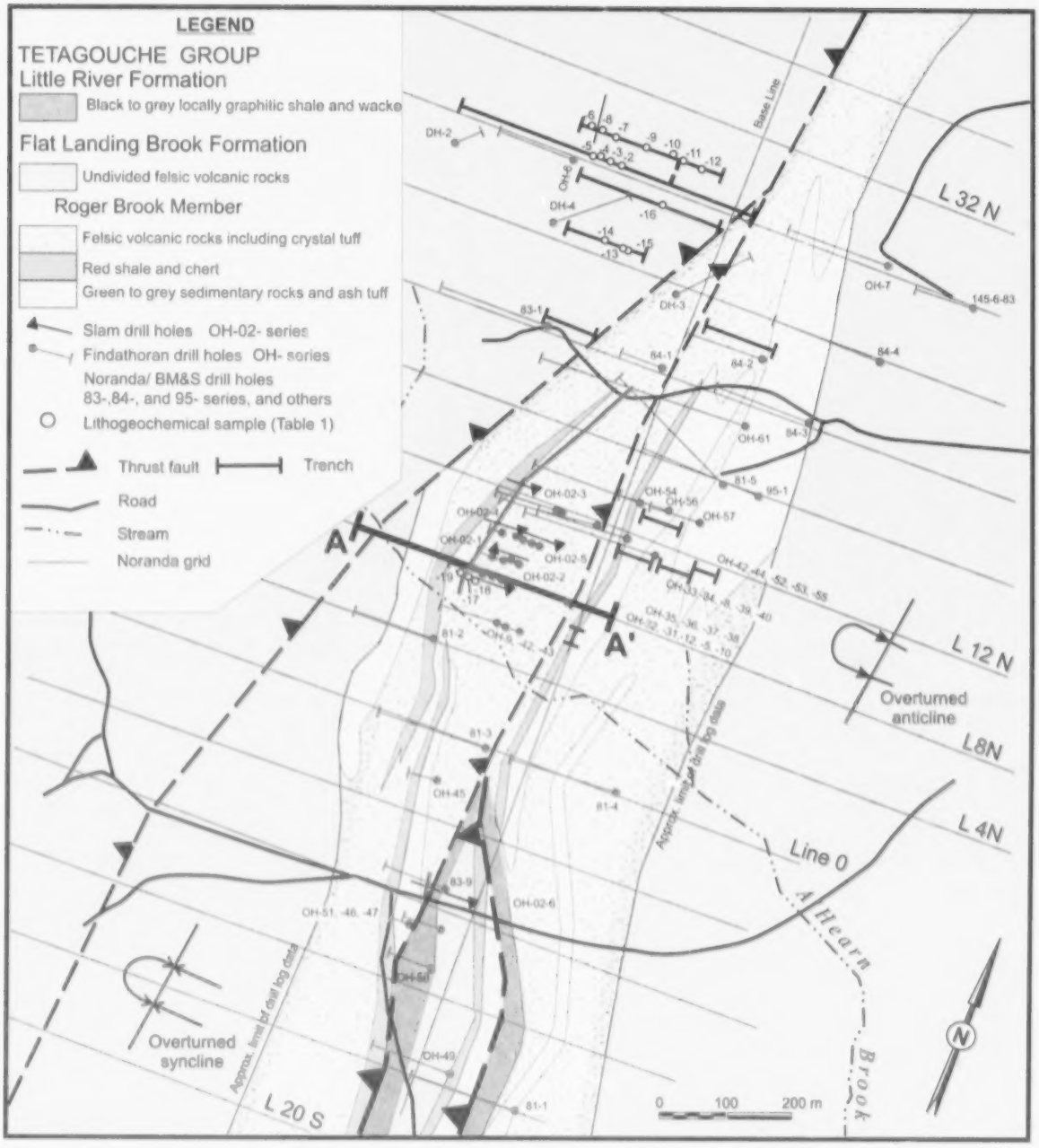


Figure 3. Detailed geology with trench and diamond drill-hole locations at the A'Hearn Brook deposit. See Figure 2 for location. Data for lithogeochemical samples are listed in Table 1. Thick red line identifies sulphide lens. Note that the vergence of the two eastern thrusts are opposite to that indicated in Figure 2.

volcanic rocks (McCutcheon *et al.* 2001). Nine deposits have reached either production or an advanced stage of pre-production development; the most famous deposit is the currently producing Brunswick No. 12 mine (> 290 000 000 t of massive sulphide resource prior to mining), located 25 km southwest of Bathurst (Figure 1).

As currently understood (Figure 1), the Bathurst Mining Camp comprises five major stratigraphic subdivisions, namely: the Miramichi, Sheephouse Brook, Tetagouche, California Lake and Fournier groups (see McCutcheon *et al.* 1993; Thomas *et al.* 2000; van Staal *et al.*, in press, and references therein for detailed descriptions). The Miramichi Group includes Cambro-Ordovician siliciclastic rocks, whereas the Fournier Group is dominated by ocean floor mafic volcanic rocks. The three remaining groups, i.e., Sheephouse Brook, Tetagouche, and California Lake groups, all contain felsic and mafic volcanic and sedimentary rocks. The majority of the deposits within the camp (32 of 46), are hosted by the Tetagouche Group. The Tetagouche Group comprises four formations that are, in ascending stratigraphic order: Nepisiguit Falls, Flat Landing Brook, Little River and Tomogonops formations. The majority of the Tetagouche Group deposits (24) are associated with the Nepisiguit Falls Formation and the remainder with the stratigraphically higher Flat Landing Brook Formation (McCutcheon *et al.* 2001). Chemically precipitated iron-formation overlies, and is laterally continuous with, many of the deposits hosted by the Nepisiguit Falls Formation (Peter and Goodfellow 1996). In contrast, iron formation is absent or poorly developed in deposits hosted by the Flat Landing Brook Formation.

During closure of the back-arc basin in the Late Ordovician to Early Silurian, the rocks of the Bathurst Mining Camp were dismembered and deformed in a subduction complex. The resulting tectono-stratigraphic relationships are invariably complex because at least five generations of folding are evident. However, in general terms, the Camp can be divided into four major thrust nappes that internally contain numerous stratigraphic cut-outs and/or repetitions related to subsidiary thrust faults.

The A'Hearn Brook deposit is hosted by sedimentary and volcanic rocks of the Flat Landing Brook Formation and occurs on the southeast limb of the Tetagouche Antiform (Figure 1), a major F_4 fold that controls rock unit distribution and the overall shape of the Camp. This area is structurally complex, with locally intense layer-parallel shear. According to van Staal *et al.* (2002) the A'Hearn Brook deposit and its immediate host rocks occur within a narrow thrust-bound nappe that also incorporates sedimentary rocks assigned to the Nepisiguit Falls Formation (Figure 2). Felsic volcanic and related sedimentary and mafic volcanic rocks of the Flat Landing Brook Formation occur to the east and west of the deposit, in the hanging wall of the folded thrust (Figure 2).

Structure

In the A'Hearn Brook area (Figure 2), geologic units and structural fabrics strike north–south, have moderately steep to subvertical dips (to either the east or west). Deformation is locally intense. At least two penetrative fabrics are evident in outcrop as well as drill core, and are interpreted to represent the S_0/S_1 composite cleavage and S_2 cleavage. Numerous thrust faults related to D_1 and D_2 deformational events also trend north–south and commonly mark unit contacts.

Mapping by van Staal *et al.* (2002) places the A'Hearn Brook deposit on the west limb of a tight north–south-trending, east-dipping F_2 antiform. The later has folded an earlier thrust fault that is interpreted as an out-of-sequence D_2 structure as it locally emplaces Flat Landing Brook rocks over older rocks assigned to the Nepisiguit Falls Formation. The deposit lies in the footwall of the thrust (Figure 2). A marker horizon containing red shale and chert at A'Hearn Brook has been correlated with similar rocks at the Strachens Lake occurrence located approximately 3 km to the west, thereby outlining the large-scale, north–south-trending, overturned synform shown in (Figure 2).

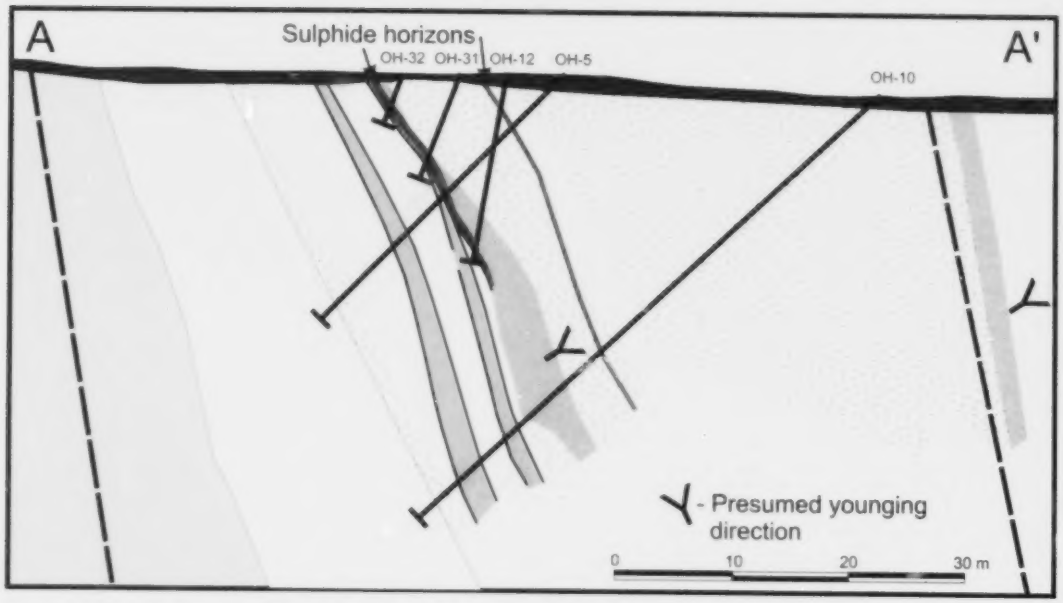


Figure 4. Cross section A–A' through the A'Hearn Brook massive sulphide deposit. See Figure 3 for the legend and location of the section line. Section is modified from MacKenzie (1983).

DETAILED STRATIGRAPHY

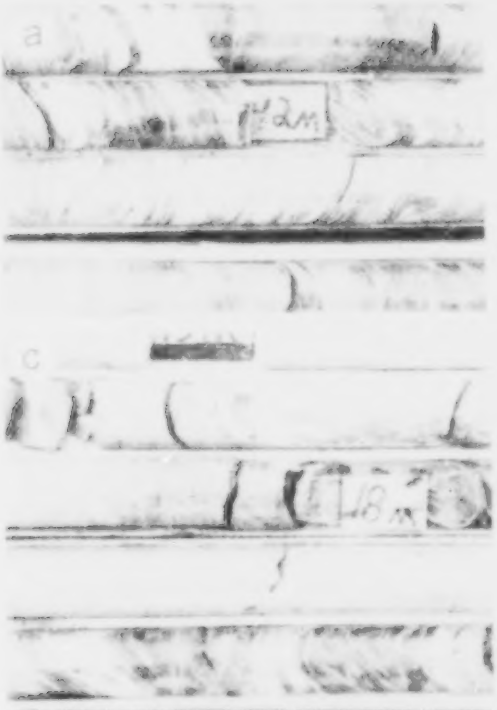
The stratigraphy described in this section is based on recent work by Slam Exploration Ltd., and involved examination of drill core that intersects the mineralized horizon over a strike length of approximately 600 m, and trenches approximately 500 m north of this drilling (Figure 3). However, these data only cover a limited (<150 m) stratigraphic thickness; consequently, compiled data from drill logs were used to construct a map and cross section (Figures 3 and 4, respectively).

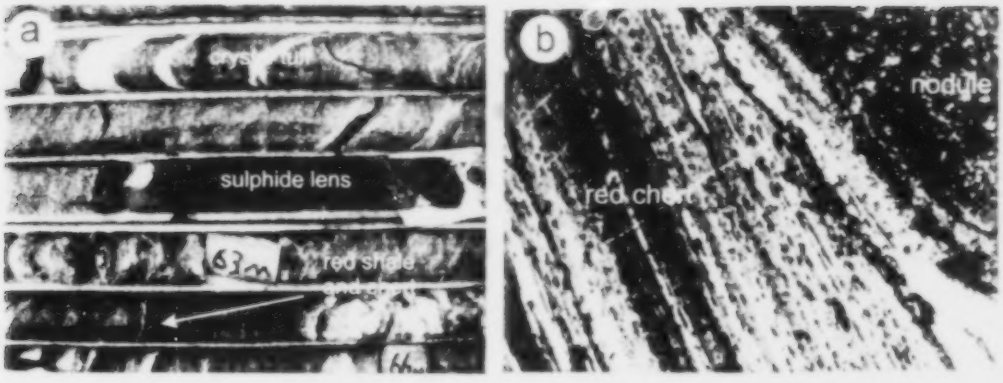
The stratigraphic succession in the immediate vicinity of the Slam Exploration Ltd. work comprises three steeply east-dipping units that are locally tectonically interleaved. These are: Flat Landing Brook Formation (undivided), Roger Brook Member, and Little River Formation.

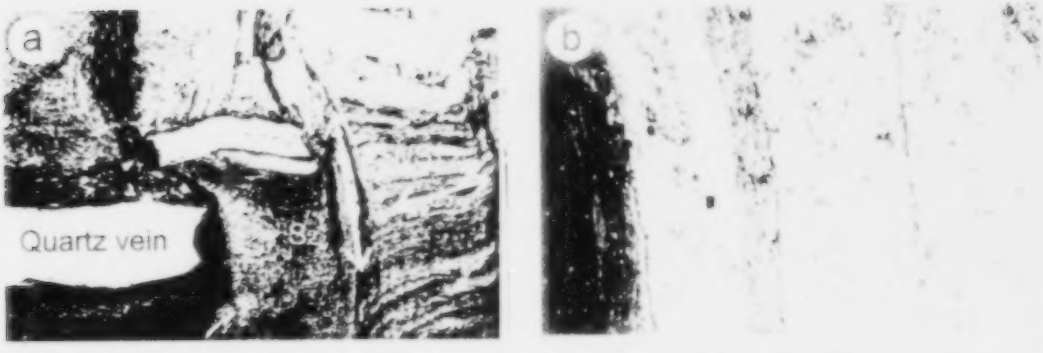
The Flat Landing Brook Formation (undivided) comprises aphyric to sparsely feldspar-phyric rhyolite and related volcaniclastic and sedimentary rocks. This unit underlies most of the area outside of the folded thrust (Figures 2 and 3).

The Roger Brook Member (Flat Landing Brook Formation) is divided into three subunits (Figures 3 and 4). The first contains predominantly thin-bedded, dark greenish grey feldspar crystal tuff and ash tuff, and buff to pink, aphyric to sparsely feldspar-phyric rhyolite, with minor sedimentary rocks (Figure 5a, c). The feldspar crystals are commonly broken, indicating emplacement via explosive rather than effusive processes, and are weakly to moderately sericite-altered. Locally, the groundmass in these rocks is almost completely altered to sericite with variable amounts of carbonate, and some chlorite and minor pyrite (Figure 5b). There is ample evidence of high strain in these rocks, with pressure shadows and pulled-apart feldspar crystals.

The second subunit comprises interlayered red shale and minor red chert that lies approximately 3 m to the west, i.e., stratigraphically above the sulphide lens in drill holes OH-02-01 through


a
b
c


a
sulphide lens
63m
red shale
b
nodule


a
Quartz vein
b

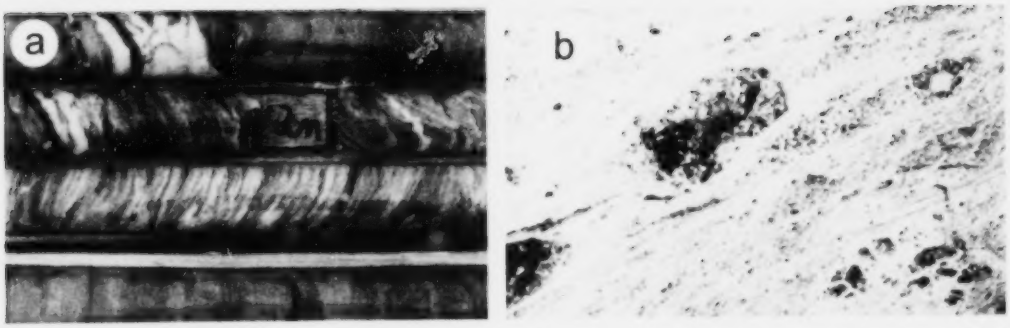


Figure 5. Host rock types intersected in drilling at the A'Hearn Brook deposit: (a) interlayered ash and crystal tuff from diamond-drill hole OH-02-04 at 42 m; (b) photomicrograph of sericite-altered crystal tuff (crossed nicols, field of view is approximately 2.6 mm); (c) buff to pink, sparsely feldspar-phyric rhyolite and rhyolite fragmental rocks from diamond-drill hole OH-02-06 at 18 m. Core diameter is approximately 4.5 cm.

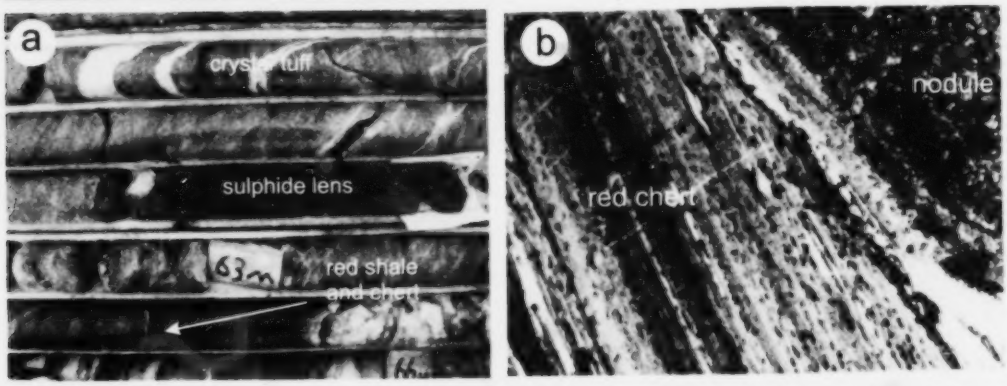


Figure 6. Chemical exhalite at the A'Hearn Brook deposit: (a) red chert and siltstone in the immediately hanging wall; (b) photomicrograph of red chert containing a manganese nodule (field of view 2.6 mm, polarized light). Sample is from drill hole OH-02-06 at 95.3 m.

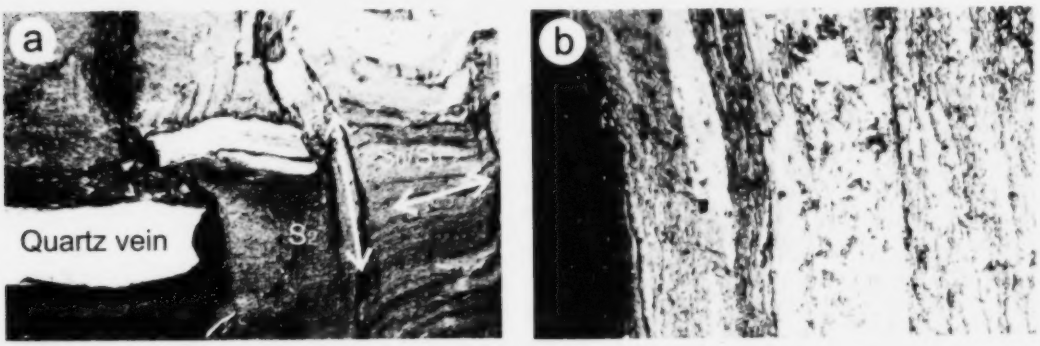


Figure 7. Little River Formation rocks: (a) black shale in drill hole (OH-02-06 at 60 m); (b) photomicrograph of black shale with two penetrative fabrics, and disrupted quartz vein parallel earlier fabric. Grit bed is interlayered with shale. Sample is from drill hole OH-02-06 at 60 m. For both, plane polarized light and a field of view of 2.6 mm.

OH-02-05 (Figure 6a). Small manganese nodules are locally developed in this unit (Figure 6b). Similar red rocks also occur immediately east of the sulphide horizon in drill hole OH-10 (Figure 4). These rocks are locally interbedded with green mudstone and minor crystal tuff similar to rocks described above. This red unit makes a good stratigraphic marker that can be traced along strike to the south (Figure 2). Very narrow high-grade massive sulphide lenses, commonly less than 1 m in thickness, occur within or immediately below this unit (Figures 6a).

The third subunit comprises dark green to grey sedimentary rocks and minor interlayered ash tuffs.

The Little River Formation consists of black, locally graphitic shale and/or tectonic mélange (Figure 7) that is restricted to the southern part of the deposit where it was identified in drill holes OH-02-06 and 81-1 (Figure 3). In drill hole OH-02-06, this unit occurs above the Roger Brook crystal tuff and is in tectonic (?) contact with fine-grained, green mudstone that hosts the sulphide lens. To the west of the sulphide lens, the green mudstone grades into a red siltstone and chert sequence (Roger Brook Member), similar to that observed in drill holes OH-02-01 through OH-02-05.

Although no definitive stratigraphic topping indicators have been identified in trenches or drill cores, it is assumed that the deposit is overturned to the west and youngs in that direction. This is based on two assumptions, namely:

1. Although the Roger Brook Member occurs at the base of the Flat Landing Brook Formation at the type locality, elsewhere in the Bathurst Mining Camp, it typically occurs near the top of the Flat Landing Brook Formation.

2. The transition from anoxic (black shale and massive sulphides) to oxic conditions is known to occur after mineralization or distal to and synchronous with mineralization in other deposits within the camp, i.e., Louvicourt (Gummer 1966). Therefore, if the A'Hearn massive sulphide body formed from stratiform chemical exhalative sediment, it must young to the west as the overlying red sedimentary rocks signify transition to an oxygenated water column.

The latter assumption may or may not be valid.

The simple stratigraphic sequence described above is repeated in at least three thrust-bound slices in the immediate vicinity of the deposit (Figures 3 and 4). However, the massive sulphides only occur in one of these slices.

LITHOGEOCHEMISTRY

A total of 16 trench samples and 23 drill core samples were collected for lithogeochemical analysis. Analyses of URN 120 series samples were conducted at Activation Laboratories Ltd., whereas OH-02 series samples were carried out at Acme Analytical Laboratories Ltd. These data are listed in Table 1. In addition to data collected during this study, three samples of massive sulphide, one of shale and one of feldspar-phyric rock (all compiled from McClenaghan 2002), are also included in Table 1. The locations of the trench samples and the position of drill holes from which samples were collected are plotted on Figure 3.

Felsic volcanic rocks

Major-element chemistry for the purpose of rock type determination has traditionally been of little use in the Bathurst Mining Camp. This is because under conditions of greenschist-grade metamorphism and hydrothermal alteration, which are pervasive in the camp, the major oxides,

Table 1. Lithological data from the A'hearn Brook Zn–Pb–Cu–Ag Deposit.

Sample	URN 120-10	OH-02-04-26.3m	URN 120-16	URN 120-09	OH-02-06-107m	OH-02-04 43m	-OH-02-06-14.5m	OH-02-06-39.8m	OH-02-04-68.9m	OH-02-04-12m
Unit	FLBu	RB	FLBu	FLBu	RB	RB	RB	RB	RB	RB
Composition	AND	AND	AND	RD	RD	RRDD	RRDD	RRDD	RRDD	
Rock Type	rhy frag	frag xl tf	ash tuff	aphy rhy	xl lap tf	sericitic ash tf	xl tf	xl tf	xl lap tf	ash xl tf
wt. %										
SiO_2	64.82	72.89	91.84	73.51	59.69	82.63	72.15	71.01	70.22	68.31
TiO_2	1.05	0.72	0.10	0.62	0.43	0.21	0.51	0.56	0.35	0.54
Al_2O_3	14.71	11.01	2.20	11.66	10.64	7.18	12.73	13.73	14.02	14.41
$Fe_2O_3^{(tot)}$	4.98	4.21	1.92	3.73	3.39	2.35	3.65	4.05	3.50	3.54
MnO	0.22	0.24	0.07	0.12	0.38	0.15	0.07	0.06	0.05	0.04
MgO	3.49	2.12	1.16	2.05	3.04	1.70	1.05	3.14	2.29	1.96
CaO	0.29	0.23	0.03	0.13	6.30	0.14	2.98	0.26	1.25	0.16
Na_2O	2.89	0.05	0.07	1.73	0.79	-0.01	1.95	2.42	1.97	2.57
K_2O	4.38	5.22	0.50	4.93	4.99	2.79	2.77	1.94	3.32	5.68
P_2O_5	0.25	0.16	0.04	0.15	0.11	0.03	0.11	0.13	0.05	0.11
LOI	2.81	2.76	1.15	1.82	9.67	3.10	2.28	2.78	3.21	1.84
ppm										
Ag	0.63	-0.30	0.50	0.52	-0.30	-0.30	0.42	0.67	-0.30	0.67
As	15.0	19.0	31.0	19.0	28.8	3.5	4.5	3.0	3.5	5.3
Au	-2	-2	3	2	-2	-2	-2	-2	5	-2
Ba	727	793	42	743	851	154	707	611	856	624
Be	2	3	1	1	2	2	4	3	4	3
Bi	-0.10	-0.10	0.25	0.21	-0.10	0.28	0.30	0.14	0.63	0.19
Cd	-0.30	2.90	9.41	-0.30	-0.30	-0.30	-0.30	0.39	-0.30	-0.30
Co	10.4	8.0	9.2	6.0	7.0	2.0	5.0	5.0	3.0	3.0
Cr	25.3	20.0	19.4	28.2	17.0	6.0	5.0	-5.0	-5.0	-5.0
Cs	1.69	2.56	0.22	4.43	3.13	1.90	3.34	2.59	8.20	2.20
Cu	55.62	20.87	89.55	15.58	21.74	4.70	8.18	6.12	4.90	8.58
Ga	20.82	15.25	5.08	14.87	13.64	9.87	20.67	21.88	19.59	19.99
Hf	5.70	4.60	0.72	5.36	4.16	3.17	8.76	9.97	8.30	11.80
Mo	-2	2	9	-2	-2	-2	4	-2	2	5
Nb	10.6	10.8	-0.2	9.1	11.4	11.0	16.9	19.6	14.9	19.0
Ni	7.7	6.0	22.1	6.9	6.8	1.3	-1.0	-1.0	-1.0	-1.0
Pb	24.0	1098.0	176.8	62.0	34.8	5.1	11.5	11.5	16.4	13.3
Rb	122.58	168.57	18.92	150.21	124.28	102.13	168.07	85.85	135.37	143.52
S	0.03	0.27	0.79	0.01	0.11	0.29	0.00	0.00	0.00	0.06
Sb	3.10	2.30	1.40	3.10	2.30	0.80	1.90	1.60	3.00	1.80
Sc	20.3	15.6	2.8	13.9	12.3	6.7	12.4	12.8	7.7	12.9
Sn	3.17	3.04	2.08	5.77	2.73	2.34	5.50	5.85	6.98	6.35
Sr	52	44	2	47	173	15	268	37	53	72
Ta	1.11	1.06	0.19	0.97	0.97	0.80	1.52	1.66	1.53	1.98
Th	10.14	9.71	1.76	9.73	12.04	7.80	18.56	20.50	20.51	21.10
Tl	0.74	1.57	0.28	0.63	1.03	0.59	0.87	0.78	1.14	1.33
U	3.84	4.53	0.59	3.09	5.18	0.76	4.11	4.63	3.11	5.34
V	185	111	16	82	66	-5	19	21	11	19
W	3.0	3.3	2.0	4.0	4.8	1.8	4.5	2.0	1.9	2.1
Y	41.00	27.32	6.00	46.00	36.53	39.08	69.66	59.87	57.57	70.69
Zn	318	1349	2041	265	84	91	147	373	44	178
Zr	190.00	165.16	24.00	164.00	174.68	106.75	359.03	432.54	307.62	477.08
La	36.49	28.15	7.97	31.67	32.80	20.96	51.49	25.46	48.25	55.60
Ce	73.86	58.12	19.60	64.56	68.60	51.43	107.14	86.31	101.67	121.16
Pr	8.82	6.55	1.85	7.75	7.69	4.83	12.14	6.26	10.88	14.04
Nd	36.17	25.96	7.11	30.78	30.07	18.96	47.82	24.94	41.96	55.94
Sm	7.07	5.86	1.51	6.82	6.62	4.48	10.98	6.04	9.36	12.44
Eu	1.34	1.22	0.32	1.74	1.11	0.58	1.69	0.96	1.35	1.82
Gd	6.90	5.04	1.43	7.36	6.01	4.49	10.63	5.99	8.57	11.43
Tb	1.22	0.86	0.23	1.38	1.04	0.90	1.88	1.32	1.53	2.03
Dy	7.23	5.01	1.26	8.30	6.18	5.97	11.29	9.21	9.31	12.35
Ho	1.45	1.03	0.24	1.67	1.32	1.37	2.42	2.15	2.00	2.56
Er	4.01	3.24	0.64	4.38	4.12	4.66	7.44	7.19	6.30	7.93
Tm	0.59	0.47	0.09	0.64	0.60	0.76	1.09	1.12	0.91	1.19
Yb	3.48	2.97	0.54	3.78	3.67	4.83	6.52	6.81	5.58	7.16
Lu	0.50	0.43	0.08	0.50	0.54	0.74	0.94	1.01	0.80	1.05

Notes: Samples are from trenches and drill core collected in 2001 and 2002. Surface samples are located in Figure 3. URN series samples were analysed at Activation Laboratories Ltd., Ancaster, Ontario and OH series samples at Acme Analytical Laboratories, Vancouver, B.C. Composition is based on Zr/Ti vs. Nb/Y (Winchester and Floyd 1977). Data preceded by "-" are below detection limits.

Table 1 (continued)

URN 120-17 RB RRDD dacite	OH-02-04-59.5m RB RRDD xl tf	OH-02-04-63.2m RB RRDD xl tf	URN 120-04 FLBu RRDD rhy frag	URN 120-05 FLBu RRDD grey aphy rhy	URN 120-18 RB RRDD aph rhy	URN 120-03 FLBu RRDD spherulitic rhy	URN 120-02 FLBu RRDD aph rhy	OH-02-05-47.8m RB RRDD xl lap tf	OH-02-5-38m RB xl ash tf
75.35	69.96	71.89	66.47	76.45	75.30	64.61	74.86	68.52	73.37
0.36	0.30	0.30	0.44	0.34	0.30	0.51	0.37	0.34	0.28
12.18	14.75	13.77	16.72	10.96	12.95	18.44	11.96	16.03	13.68
2.71	2.59	3.06	3.42	1.29	1.81	2.16	1.32	2.38	1.96
0.04	0.05	0.11	0.06	0.01	0.02	0.06	0.01	0.17	0.02
2.12	3.60	3.35	2.26	0.22	0.57	2.36	0.34	4.19	2.99
0.42	0.40	0.46	0.02	0.02	1.05	0.07	0.02	0.33	0.09
4.65	1.10	2.10	0.09	0.16	4.69	0.12	0.25	1.62	1.27
0.80	3.70	2.31	7.57	9.05	2.24	8.94	9.11	3.03	3.34
0.07	0.04	0.04	0.08	0.09	0.05	0.10	0.06	0.05	0.04
1.66	3.44	2.93	2.93	0.65	1.26	2.76	0.81	3.54	2.63
0.34	-0.30	-0.30	1.45	1.12	0.65	1.52	1.16	-0.30	-0.30
4.0	4.2	2.5	50.0	54.0	3.0	8.0	21.0	9.1	3.8
2	2	9	5	9	2	2	2	2	-2
174	893	598	749	1613	388	857	2195	1333	814
1	4	3	6	2	3	8	2	4	4
-0.10	-0.10	0.39	1.71	0.60	0.14	0.29	0.31	0.90	0.20
0.30	-0.30	-0.30	-0.30	-0.30	0.57	-0.30	-0.30	1.40	1.25
7.4	2.0	6.0	2.1	2.7	2.6	3.4	1.1	5.0	-1.0
10.3	8.0	-5.0	10.6	14.1	3.9	4.7	7.9	-5.0	-5.0
1.11	2.64	2.98	2.54	1.03	1.99	1.22	1.05	7.38	2.53
50.88	25.07	51.44	39.66	22.08	14.27	11.71	14.79	33.95	6.97
16.20	22.84	17.52	30.91	13.99	20.20	40.35	17.65	20.88	18.66
9.98	8.06	7.61	12.72	9.52	9.82	15.47	11.19	8.50	7.93
-2	4	-2	6	5	-2	-2	3	-2	2
10.9	16.5	14.4	19.8	14.0	13.1	27.4	21.6	17.3	15.3
5.9	-1.0	2.3	-1.0	-1.0	1.1	-1.0	-1.0	-1.0	-1.0
328.5	8.9	12.3	26.2	13.1	294.4	7.2	19.8	127.0	98.2
27.05	121.36	89.58	300.02	184.03	89.37	313.32	195.72	121.40	105.54
0.01	0.01	0.01	0.00	0.40	0.01	0.01	0.01	0.01	0.01
2.70	2.30	2.00	4.40	2.70	1.80	1.90	1.70	3.60	2.80
7.3	7.4	6.8	14.4	10.0	7.1	17.3	10.8	8.1	7.1
5.21	6.39	5.69	10.49	4.76	5.98	10.41	6.44	7.09	5.65
61	42	38	6	49	119	12	50	71	25
1.14	1.62	1.55	1.55	1.38	1.36	2.66	1.69	1.77	1.57
14.50	21.89	20.90	18.90	15.46	17.07	25.71	18.25	24.01	20.91
0.29	0.78	0.73	1.07	1.68	0.44	0.83	1.60	1.35	1.04
2.67	3.53	4.61	9.91	4.13	4.35	7.59	5.53	1.81	4.60
20	9	6	26	13	11	16	16	5	10
3.0	3.8	3.2	1.0	5.0	-1.0	7.0	4.0	1.6	2.7
58.00	60.47	38.84	68.00	51.00	45.00	89.00	72.00	29.56	51.07
338	222	54	84	21	136	59	55	231	186
339.00	287.70	283.73	418.00	323.00	295.00	503.00	362.00	337.82	286.05
115.46	52.92	51.19	78.41	43.59	45.31	70.85	58.09	43.45	39.95
173.26	110.00	111.73	159.48	90.85	93.26	150.71	122.61	93.48	83.46
25.89	12.04	11.93	18.93	10.38	10.80	17.69	14.26	10.46	9.25
98.72	45.77	45.20	73.91	41.00	41.49	69.71	56.43	39.41	35.52
18.02	9.91	9.61	13.28	8.41	8.17	14.21	11.49	8.02	7.97
2.32	1.31	1.29	2.45	1.38	1.33	2.06	1.86	1.10	1.11
16.06	9.00	8.14	11.77	8.33	7.65	13.61	11.45	6.40	7.66
2.24	1.61	1.40	1.97	1.52	1.38	2.60	2.12	1.00	1.41
11.38	9.94	8.20	12.04	8.90	8.44	16.17	13.10	5.58	8.77
2.20	2.05	1.68	2.58	1.87	1.80	3.40	2.69	1.13	1.86
6.46	6.26	5.46	7.82	5.54	5.26	9.97	7.49	3.63	5.78
0.94	0.91	0.93	1.19	0.83	0.79	1.52	1.10	0.57	0.88
5.85	5.40	6.37	7.60	5.21	5.01	9.53	6.79	3.87	5.33
0.86	0.77	0.97	1.13	0.79	0.72	1.36	0.94	0.60	0.79

Notes (continued) Abbreviations: AND – andesite; aphy – aphyric; FLB – Flat Landing Brook; FLBu – Flat Landing Brook undivided; frag – fragmental; lap – lapilli; LR – Little River Formation; RB – Roger Brook Member; RD – rhyodacite/dacite; rhy – rhyolite; RRDD – rhyolite/ rhyodacite/dacite; sed – sedimentary; sil – siliceous; tf – tuff; xl – crystal.

Table 1 (continued)

Sample	OH-02-05-42.3m	URN 120-08	URN 120-07	OH-02-04-41m	OH-02-04-38.5m	OH-02-06-101.8m	URN 120-13	URN 120-14	URN 120-15
Unit	RB	FLBu	FLBu	RB	RB	RB	FLBu	FLBu	FLBu
Composition									
Rock type	xl ash tf	aph rhy	ash tuff	ash xl tf	rhy	ash tf	ash tuff	phyllite	ashy sed 3% py
wt. %									
SiO_2	62.71	79.88	71.47	74.52	77.41	76.19	84.89	69.57	69.11
TiO_2	0.38	0.15	0.22	0.19	0.14	0.24	0.09	0.43	0.22
Al_2O_3	18.72	9.66	14.21	12.78	10.28	10.52	7.20	15.60	14.17
$Fe_2O_3^{(tot)}$	2.87	1.59	1.89	2.11	1.56	2.39	2.00	2.76	3.01
MnO	0.07	0.03	0.02	0.10	0.09	0.02	0.02	0.07	0.09
MgO	4.03	0.84	1.01	1.83	0.49	3.41	0.43	2.29	3.09
CaO	0.77	0 02	-0.01	0.08	0.13	0.42	0.01	0.08	0.03
Na_2O	1.75	0.92	0.11	-0.01	0.13	0.08	0.10	0.09	0.13
K_2O	4.20	4.05	8.65	5.84	7.98	2.85	3.35	6.26	7.05
P_2O_5	0.05	0.03	0.03	0.03	0.03	0.04	0.02	0.10	0.05
LOI	4.05	1.69	1.71	2.44	1.44	3.09	1.52	2.95	3.00
ppm									
Ag	-0.30	0.87	0.95	-0.30	-0.30	0.38	1.46	0.68	0.46
As	3.5	38.0	43.0	4.3	31.9	1.8	31.0	13.0	5.0
Au	-2	4	4	-2	-2	2	16	-2	2
Ba	1158	611	1440	764	1744	1072	873	732	1507
Be	6	2	5	3	1	3	2	4	2
Bi	0.73	1.28	0.67	-0.10	0.11	-0.10	0.34	-0.10	-0.10
Cd	-0.30	-0.30	-0.30	-0.30	-0.30	-0.30	-0.30	-0.30	-0.30
Co	3.0	1.5	1.4	2.0	2.0	1.0	1.4	2.1	3.0
Cr	-5.0	2.3	-0.5	-5.0	9.0	-5.0	3.2	16.5	2.0
Cs	4.25	1.17	1.09	2.64	1.59	2.63	0.91	4.20	5.68
Cu	6.91	39.61	47.46	5.34	5.82	4.90	733.48	33.50	47.77
Ga	24.95	15.75	31.74	16.04	5.61	16.04	14.23	24.72	21.14
Hf	9.27	6.16	9.87	7.01	6.00	8.17	4.59	9.20	10.10
Mo	-2	6	5	3	9	-2	2	-2	-2
Nb	20.7	10.9	20.2	15.0	12.5	17.1	7.9	16.0	20.6
Ni	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	15.0	1.7
Pb	22.6	47.9	95.0	36.8	26.2	9.3	39.7	94.3	77.9
Rb	150.31	159.66	273.87	223.07	149.40	108.28	92.54	288.13	223.33
S	0.00	0.01	0.02	0.06	0.54	0.00	0.87	0.01	0.01
Sb	3.20	2.70	2.80	1.70	1.70	1.50	3.80	4.40	1.90
Sc	9.5	13.6	22.8	8.0	4.7	8.1	9.4	17.3	17.6
Sn	8.02	3.98	10.52	5.42	1.67	4.58	2.50	5.24	4.92
Sr	64	12	22	13	76	27	13	9	36
Ta	1.99	1.25	1.96	1.54	1.36	1.50	1.00	1.58	1.94
Th	28.06	14.35	21.05	18.47	14.34	17.35	9.99	17.64	19.87
Tl	2.76	1.01	1.10	1.60	2.05	0.54	0.52	1.79	2.19
U	4.92	2.46	3.38	3.70	4.29	3.24	2.29	2.89	4.43
V	12	-5	9	6	6	-5	-5	42	7
W	2.6	3.0	5.0	1.9	2.0	1.3	2.0	5.0	3.0
Y	58.40	34.00	41.00	45.63	38.59	56.75	27.00	68.00	88.00
Zn	190	58	57	66	37	60	186	130	286
Zr	383.88	178.00	285.00	237.38	186.71	329.93	140.00	276.00	297.00
La	60.62	30.43	64.76	53.64	30.08	46.69	27.42	59.82	72.85
Ce	128.99	65.93	137.51	113.59	66.75	98.03	58.19	118.56	161.06
Pr	14.13	7.34	15.23	12.29	7.33	11.02	6.54	14.87	19.55
Nd	53.87	28.41	61.21	47.28	28.10	43.08	24.89	59.02	78.08
Sm	11.66	5.53	11.49	10.12	6.14	9.71	4.32	11.96	14.68
Eu	1.59	0.95	1.73	2.05	0.86	1.37	0.57	2.02	1.63
Gd	10.27	5.24	9.37	8.63	5.51	8.99	3.94	11.50	12.57
Tb	1.78	0.95	1.46	1.40	1.02	1.60	0.80	1.94	2.23
Dy	10.62	5.96	8.34	7.95	6.49	9.64	5.07	11.24	14.02
Ho	2.26	1.30	1.74	1.66	1.40	2.05	1.08	2.42	2.98
Er	7.30	3.89	5.16	5.29	4.41	6.33	3.22	7.11	8.81
Tm	1.13	0.61	0.77	0.79	0.67	0.95	0.53	1.10	1.36
Yb	7.14	3.84	4.93	5.05	4.00	5.73	3.09	6.54	7.94
Lu	1.07	0.57	0.72	0.77	0.61	0.86	0.46	0.94	1.11

Table 1 (concluded)

OH-02-05-44.8m RBmb	URN 120-12 FLBu	OH-02-06-93.7m RBmb	OH-02-06-83.4m sulphides	OH-02-06-95.3m RBmb	OH-02-05-22.3m RBmb	OH-02-06-60m LR	OH-02-06-74m LR	OH-02-05-20.9m RBmb	URN 120-11 FLBu
green sed	sil sed	red siltstone	ms	red chert	black mudstone	black mudstone	black mudstone	black mudstone	tuffaceous sediments
75.38	77.79	56.97	71.14	75.41	77.36	59.24	75.73	55.32	66.89
0.29	0.40	0.48	0.63	0.36	0.22	0.74	0.57	0.40	0.92
11.12	9.88	12.14	11.68	8.20	9.98	14.33	10.79	21.73	13.97
3.82	2.54	8.85	6.15	4.91	2.46	7.55	3.26	4.69	4.64
0.19	0.04	4.55	0.46	1.07	0.22	0.34	0.16	0.42	0.17
2.75	0.93	2.32	2.09	1.51	1.51	3.75	2.34	4.29	3.36
0.80	0.03	1.85	0.48	0.44	0.07	1.40	0.63	0.06	0.29
0.13	0.31	1.77	0.40	1.73	-0.01	1.30	1.64	-0.01	2.63
2.70	5.19	3.10	3.47	1.56	4.49	2.67	2.09	8.30	4.62
0.09	0.11	0.19	0.22	0.10	0.04	0.11	0.13	0.05	0.23
3.04	1.76	7.70	3.29	4.60	2.35	8.18	2.56	4.65	2.27
-0.30	0.37	-0.30	-0.30	-0.30	-0.30	-0.30	-0.30	0.63	0.46
2.5	42.0	25.7	41.0	204.0	8.3	75.4	10.8	7.50	9.0
-2	3	-2	-2	165	2	19	-2	-2.00	-2
777	1387	570	3812	779	524	1025	1083	549.00	673
2	1	2	6	2	3	2	3	-0.10	2
0.36	0.30	0.57	0.48	0.31	-0.10	-0.10	0.17	0.31	-0.10
-0.30	-0.30	-0.30	-0.30	-0.30	-0.30	-0.30	-0.30	5.00	-0.30
9.0	2.1	100.0	33.0	30.0	3.0	23.0	7.0	-5.00	9.5
9.0	-0.5	17.0	38.0	20.0	11.0	159.0	55.0	3.39	22.3
4.05	2.12	7.58	4.99	3.71	2.27	3.84	1.97	4.37	1.40
5.71	29.28	20.42	59.44	9.02	4.38	46.80	37.60	29.71	8.34
14.89	12.29	15.93	15.07	10.30	14.49	18.41	12.50	13.09	20.00
3.62	3.38	3.38	3.29	2.46	6.16	3.05	2.65	0.15	5.99
-2	2	-2	5	-2	-2	4	-2	-2.00	-2
10.5	3.1	13.3	10.2	8.8	13.2	9.1	7.3	25.47	10.8
14.1	-1.0	80.9	84.9	28.1	4.0	153.1	10.5	15.83	5.7
8.9	60.4	12.7	47.5	13.8	5.7	23.4	50.1	13.61	9.3
121.61	166.57	165.98	172.57	78.64	164.09	102.85	83.60	313.06	135.99
0.00	0.01	0.00	0.08	1.15	0.35	1.24	0.04	0.02	0.01
1.80	2.80	16.10	5.70	5.00	1.90	10.70	1.50	3.30	1.80
5.8	11.9	14.6	14.6	7.5	8.9	19.3	15.8	18.30	19.1
3.99	1.92	3.14	2.93	1.64	3.69	1.51	1.80	8.10	3.49
30	34	47	34	25	13	86	63	8.00	47
1.10	0.44	0.97	0.84	0.70	1.28	0.62	0.64	2.64	1.17
13.78	5.41	12.81	10.92	8.22	13.77	7.71	6.41	29.64	10.56
1.67	1.21	1.03	4.29	0.72	1.23	1.05	0.83	2.08	0.74
2.93	1.83	1.59	1.96	1.23	2.18	2.74	1.62	2.14	4.46
17	30	26	91	15	9	139	103	8.00	160
1.1	3.0	9.9	3.3	10.8	1.7	1.4	4.6	2.24	2.0
37.04	32.00	39.83	34.95	20.98	46.39	24.52	19.95	83.11	38.00
65	70	59	103	39	400	98	56	442.44	262
118.62	104.00	141.02	139.20	91.49	218.02	122.92	103.19	535.47	198.00
34.68	29.63	36.51	39.27	28.96	34.49	21.62	14.66	101.69	37.67
71.47	59.57	113.38	97.77	84.53	76.20	44.84	34.21	275.35	77.28
7.74	7.31	9.26	8.69	6.51	8.00	5.02	3.62	23.23	9.19
29.12	30.76	37.36	34.51	26.40	31.01	19.59	14.48	89.73	37.14
6.09	6.51	8.50	7.30	6.18	7.01	4.34	3.26	18.98	7.22
0.96	1.07	1.88	1.83	1.26	0.62	1.06	0.94	2.27	1.50
5.31	6.38	7.92	6.49	5.56	6.85	4.03	3.13	14.79	6.85
0.89	1.06	1.35	1.09	0.92	1.25	0.69	0.54	2.49	1.21
5.65	5.89	7.52	6.32	4.77	7.73	4.17	3.28	14.76	7.04
1.30	1.20	1.51	1.29	0.84	1.62	0.87	0.70	3.13	1.42
4.48	3.36	4.52	3.90	2.34	4.89	2.65	2.16	9.85	3.95
0.74	0.52	0.63	0.52	0.31	0.72	0.39	0.30	1.47	0.58
4.80	3.06	3.90	3.27	1.85	4.30	2.33	1.90	8.99	3.47
0.74	0.47	0.56	0.47	0.28	0.63	0.35	0.28	1.29	0.50

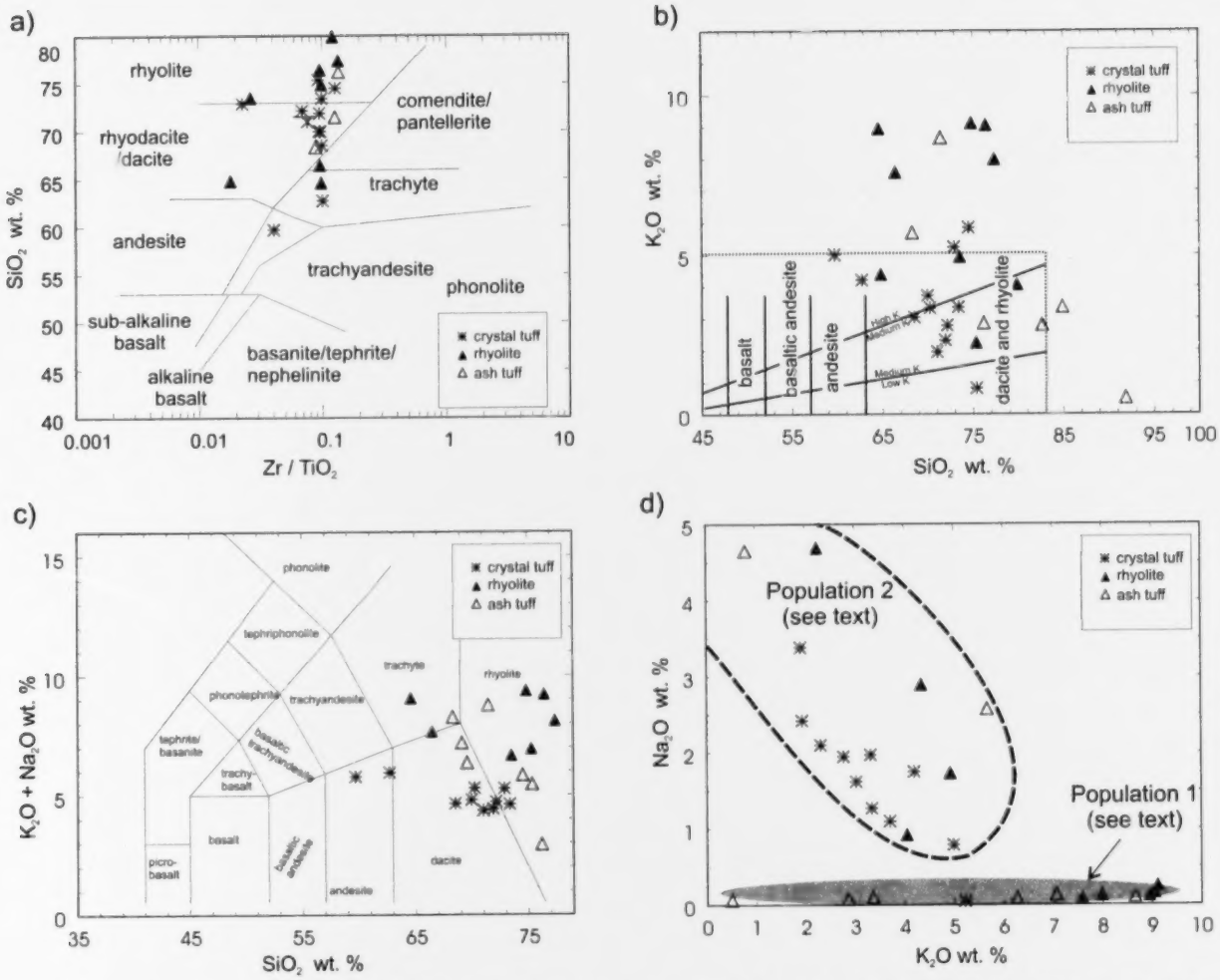


Figure 8. Major-element discrimination diagrams for volcanic rocks in the vicinity of the A'Hearn Brook volcanogenic massive sulphide deposit: (a) SiO_2 versus Zr/TiO_2 diagram (Winchester and Floyd 1977); (b) K_2O versus SiO_2 diagram (modified from Le Maitre *et al.* 1989); (c) K_2O+ Na_2O versus SiO_2 (Le Maitre *et al.* 1989); (d) Na_2O versus K_2O. Note that the dotted lines in (b) represent the original limits of this diagram.

with the possible exception of Al_2O_3 and TiO_2, are far too mobile (Lentz and Goodfellow 1993; Lentz 1996). This is confirmed by the Zr/TiO_2 versus SiO_2 and K_2O versus SiO_2 discrimination diagrams (Figure 8a and 8b, respectively). In both of these diagrams only felsic volcanic rocks, i.e., crystal tuff, ash tuff and rhyolite are plotted. Inspection of Figure 8a shows that the Zr/TiO_2 ratio falls into two distinct populations indicating two discrete magma sources, with little mixing between them. In contrast, the SiO_2 contents range from 60% to 80% or more. Figure 8b shows that many of these samples fall in the moderate to high-K category, with a large number of them containing atypically high K_2O (5–10 wt. %), well above the original limits of this diagram (c.f., Le Maitre *et al.* 1989). It should be noted that the majority of the crystal and ash tuff samples have K_2O contents that are below 4 wt. %, whereas rhyolite samples commonly have greater than 4 wt. % K_2O.

Most (n=20) of the felsic volcanic rocks plot in the dacite and rhyolite fields on the (Na_2O+K_2O) versus SiO_2 diagram (Figure 8c), with the remainder (n=4) falling in the andesite and trachyte fields.

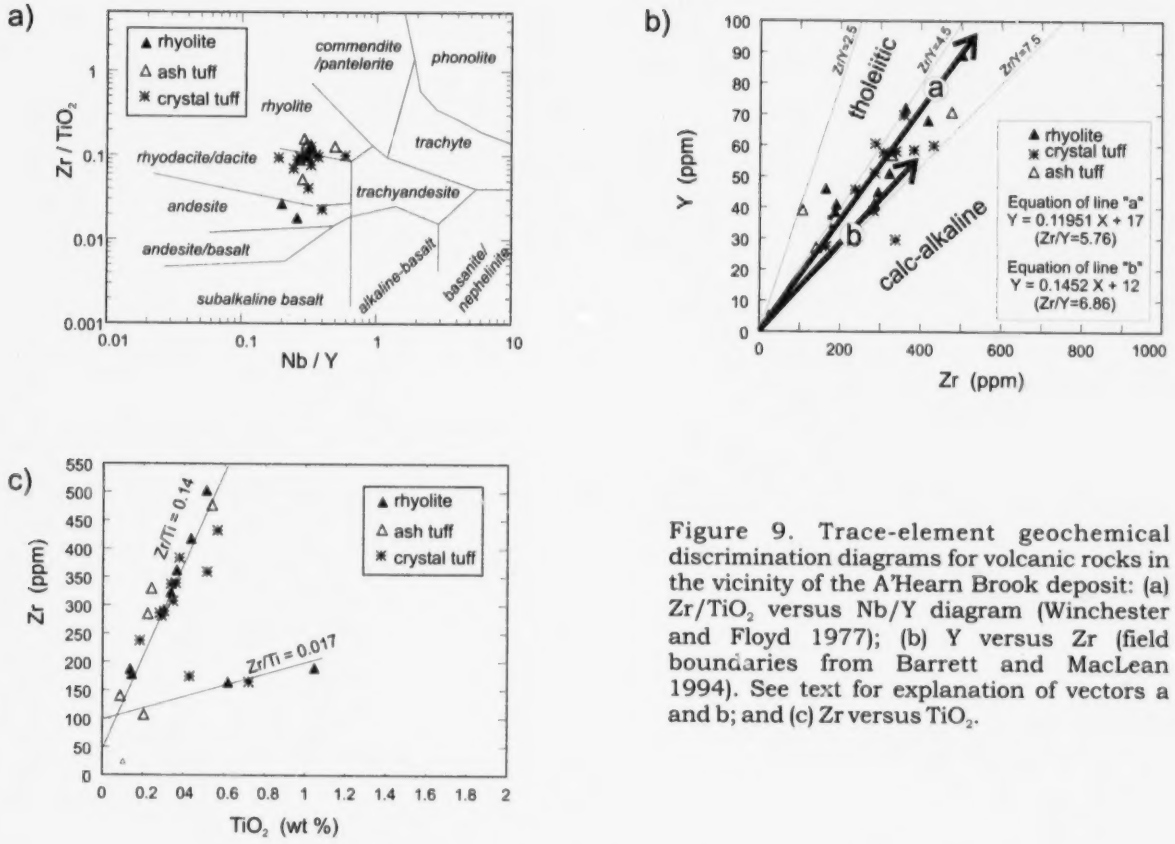


Figure 9. Trace-element geochemical discrimination diagrams for volcanic rocks in the vicinity of the A'Hearn Brook deposit: (a) Zr/TiO_2 versus Nb/Y diagram (Winchester and Floyd 1977); (b) Y versus Zr (field boundaries from Barrett and MacLean 1994). See text for explanation of vectors a and b; and (c) Zr versus TiO_2.

However, on the Na_2O versus K_2O diagram (Figure 8d) at least two distinct populations are evident. The first population is defined by very low Na_2O (< 0.5 wt. %) and variable K_2O (0.5–9 wt. %), and includes most of the ash tuff samples and half of the rhyolite samples. The second population is defined by higher Na_2O contents (> 1 wt. %) and low to moderate K_2O contents (1–6 wt. %). The second population includes the majority of the crystal tuff samples as well as two of the ash tuff samples and the remainder of the rhyolite samples.

If hydrothermal alteration is responsible for the elevated K_2O contents in these rocks, then it would be expected that permeable tuffs would be more susceptible to alteration than massive rhyolite flows. However, this is not the case because the rhyolites have higher K_2O than the tuffs.

Trace-element ratios using high-field-strength elements are of more use in protolith determination because these elements are far less mobile under the conditions of greenschist-grade metamorphism and hydrothermal alteration that prevail in these rocks. The Zr/TiO_2 versus Nb/Y diagram (Figure 9a) is one of the more useful trace-element discrimination diagrams for protolith determination. The A'Hearn Brook volcanic rocks have a bimodal distribution on this diagram. The larger of the two populations falls close to the boundary between the rhyolite and rhyolite/rhyodacite fields, whereas the second population falls well within the andesite field and/or in the lower part of the rhyodacite/ dacite field.

The Zr/Y ratio has been suggested by Rogers and van Staal (1996) as a means by which various felsic volcanic units in the Bathurst Mining Camp may be differentiated. The majority of the samples collected during this study have Zr/Y ratios that range between 2.73 and 11.43, and fall within the field of typical Flat Landing Brook rocks (Figure 9b). The best fit line through this data set as

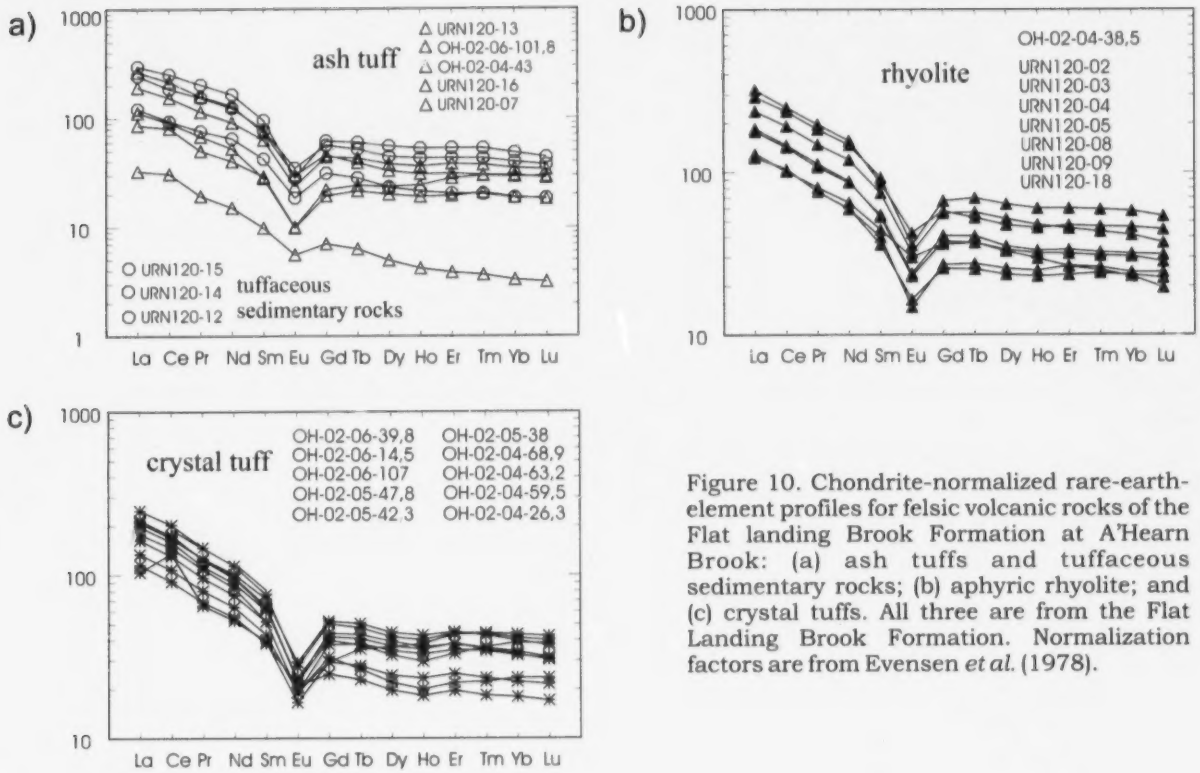


Figure 10. Chondrite-normalized rare-earth-element profiles for felsic volcanic rocks of the Flat landing Brook Formation at A'Hearn Brook: (a) ash tuffs and tuffaceous sedimentary rocks; (b) aphyric rhyolite; and (c) crystal tuffs. All three are from the Flat Landing Brook Formation. Normalization factors are from Evensen *et al.* (1978).

calculated by the least squares method corresponds to a Zr/Y ratio of 5.76 (Line "a" on Figure 9b), which falls within the transitional category of Barrett and MacLean (1994). These rocks have a Zr/Ti ratio of 0.14 (Figure 9c). The best fit line through the andesitic rocks (i.e., the three andesites in Figure 9a), as calculated by the least squares method corresponds to a Zr/Y ratio of 6.86 (line "b" on Figure 9b), which is close to the calc-alkaline field boundary (Zr/Y=7.5) of Barrett and MacLean (1994). The andesites have a much lower Zr/Ti ratio (0.017) than the more felsic samples (Figure 9c). Although, the trace-element data suggests two chemically distinct sample populations, at the hand sample scale, these rocks are not distinguishable.

The felsic volcanic rocks sampled are all enriched in light rare-earth elements relative to the heavy rare-earth elements (Figure 10). In addition, most have pronounced negative Eu anomalies that are consistent with fractional crystallization and separation of feldspar from the parent magma prior to emplacement. The rare-earth-element profiles are consistent among rhyolite, ash tuff/tuffaceous sediment and crystal tuff samples (Figures 10a, b, and c). However, one of the crystal tuff samples has a slightly positive Ce anomaly, distinguishing it from the other volcanic rocks.

Sedimentary rocks

Four samples of fine-grained sedimentary rock were collected from drill holes OH-02-06 (60 and 74 m), and OH-02-05 (20.9 and 22.3 m). Two of these (OH-02-06-60 and -74) are typical black shales containing elevated Cr, Ni, Co, V, etc. (Table 1). Trace-element ratios, specifically Zr/Cr versus V/Nb (Figure 11a), suggest that these rocks are chemically similar to sedimentary rocks in younger units of the Tetagouche Group, specifically those that postdate felsic volcanism, e.g., the Little River

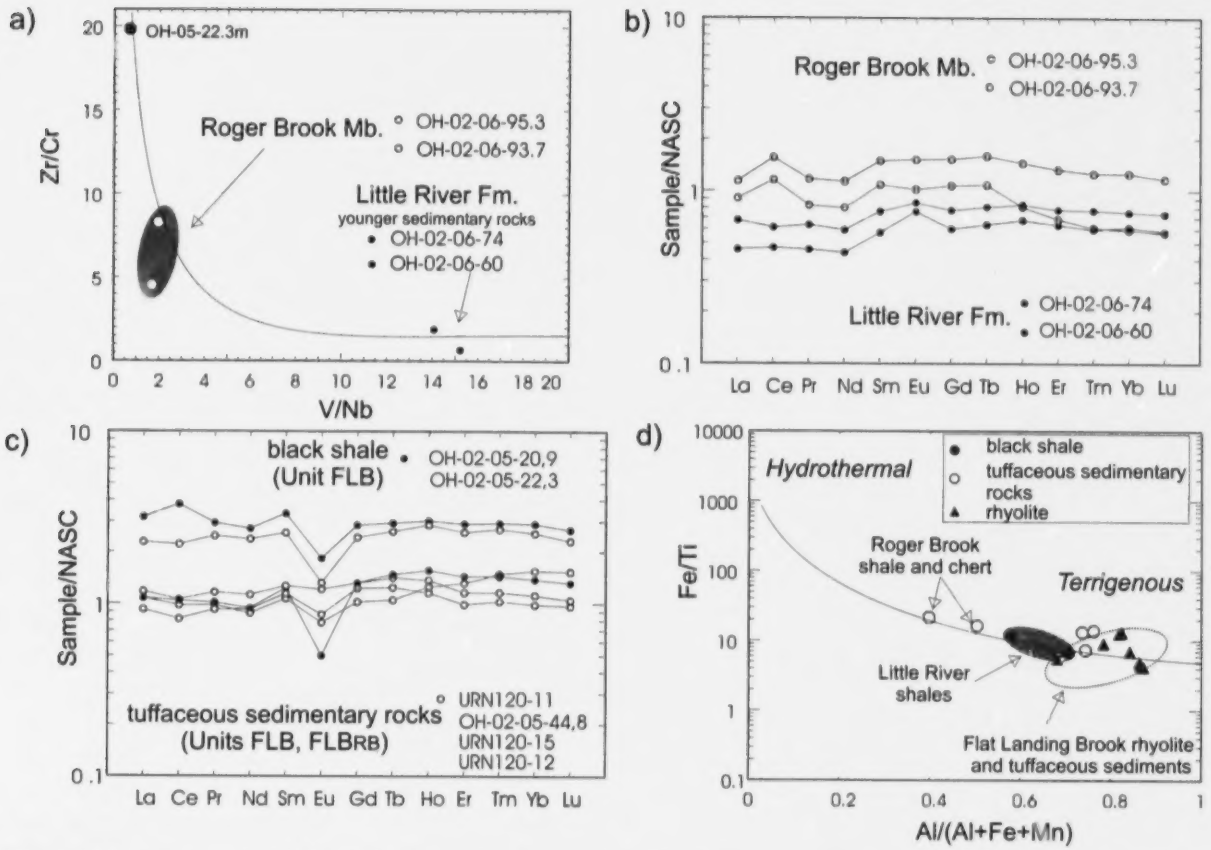


Figure 11. Trace-element discrimination and normalized rare-earth-element data for clastic and chemical sedimentary rocks from the A'Hearn Brook sulphide deposit: (a) Zr/Cr versus V/Nb discrimination diagram (McCutcheon, unpublished report); (b) North American Shale Composite normalized data from red shale and chert from the Roger Brook Member hanging wall and black shale samples from the foot wall of the A'Hearn Brook deposit; (c) North America Shale Composite normalized data from massive sulphide samples. Normalization factors in diagrams (c) and (d) are from Haskin *et al.* (1968); (d) Fe/Ti versus Al/(Al+Fe+Mn) diagram for the determination of hydrothermal input (Boström 1973).

Formation (McCutcheon 2002). The North American Shale Composite (NASC) normalized rare-earth-element profiles of samples OH-02-06-60 and -74 are relatively flat and fall very close to NASC values (Figure 11b).

The other two black shale samples (OH-02-05-20.9, and -22.3) are included in the Roger Brook Member. These have flat rare-earth-element profiles with moderate to strongly negative Eu anomalies (Figure 11c). These profiles are chemically more similar to tuffaceous sedimentary rocks in the Flat Landing Brook Formation rather than younger sedimentary units in the Bathurst Mining Camp.

Four other samples of dominantly fine-grained sedimentary rocks (URN 120-11, 120-12, 120-15 and OH-02-05-44.8) are plotted on Figure 11c. These samples evidently have a significant felsic volcanic component as their rare-earth-element profiles are flat with variably negative Eu anomalies. These rare-earth-element patterns are more akin to volcaniclastic sedimentary rocks derived from a dominantly felsic volcanic source, i.e., Flat Landing Brook Formation.

Chemical sedimentary rocks

In the Bathurst Mining Camp, chemical sedimentary rocks are divisible into two major types: (1) stratiform sulphides, and (2) oxide, carbonate and silicate facies iron formation. Massive sulphides are restricted in their lateral extent, whereas iron formation may cap sulphides and have greater lateral extent. The type/distribution and amount of iron formation developed depends on several factors, including: (a) sufficient time to accumulate, (b) the redox state of the water column; and (c) the degree to which circulation is restricted in the basin. Algoma-type iron formation is particularly well developed along the Brunswick Horizon in the eastern part of the Bathurst Mining Camp, where it can be traced along strike for more than 10 km and caps both the Brunswick No. 6 and No. 12 deposits.

Rare-earth-element data are commonly used to evaluate the amount of hydrothermal input in massive sulphides and related hydrothermal sediments (e.g., Gale *et al.* 1997). For example, it has been suggested that positive Eu anomalies and light rare-earth-element enrichment are common in chemical exhalitives that precipitated from high temperature (>350°C), acidic vent fluids (Gale *et al.* 1997). Several deposits in the Bathurst Mining Camp are known to have massive sulphide lenses and/or associated iron formation with positive Eu anomalies, e.g., Halfmile Lake (Adair 1992), Mount Fronsac North (Walker and Graves, in press), and the Brunswick No. 6 and No. 12 deposits (Peter and Goodfellow 1996).

In the A'Hearn Brook area, Algoma-type iron formation is absent. However, red siltstone and chert (Roger Brook Member) occurs stratigraphically above (?) and locally below the sulphide lens and may represent a horizon with elevated hydrothermal input. The North American Shale Composite normalized rare-earth-element profiles for these samples are relatively flat except for slight to moderately positive Ce anomalies (Figure 11b), and are similar to oxidized sedimentary rocks from elsewhere in the Bathurst Mining Camp.

The Ce anomaly is a measure of the degree of variation of the actual Ce value from the expected Ce value, as determined by the slope of the line defined by La_n and Sm_n. This is calculated by the equation outlined by Toyoda and Masuda (1991): $Ce/Ce^* = 5Ce_n / (4La_n + Sm_n)$, where n are the appropriate North American Shale Composite normalization factors for the elements Ce, La and Sm. Rare-earth-element profiles of marine sedimentary rocks can shed light on conditions prevailing at the time of deposition. It is well known that normal oxygenated seawater displays a strong negative Ce anomaly, whereas sedimentary rocks precipitated from the same water column commonly have positive Ce anomalies. The enrichment of Ce in these sediments occurs because Ce^{+3} readily oxidizes to Ce^{+4} which is highly insoluble at the neutral to high pH conditions in normal oxygenated seawater. Once Ce is oxidized to the Ce^{+4} state it readily fills available octahedral sites in precipitates (i.e., Fe–Mn oxides) or combines with oxygen to form insoluble CeO_2. The degree to which marine sediment is enriched in Ce is a function of the amount of available octahedral sites in the precipitates and/or the oxygen content of sea water.

The slightly positive Ce anomalies in these samples are attributable to the high MnO content (between 1 and 5 wt. %) of the two samples. Manganese oxide nodules are known to readily partition Ce from an oxygenated water column suggesting that they are, for the most part, hydrogenous in nature (Mills *et al.* 2001). The Fe/Mn ratios of the Roger Brook siltstone and chert samples are 1.76 and 4.14, respectively, and are at least an order of magnitude lower than all other sedimentary rocks (Table 1). On a Fe/Ti versus Al/(Al+Fe+Mn) diagram for the determination of hydrothermal input (Figure 11d), these rocks have the highest hydrothermal component relative to the other samples of sedimentary rock. However, the degree of hydrothermal input is small relative to sedimentary rocks at other deposits in the Bathurst Mining Camp (Lentz *et al.* 1995).

The elevated Co (100 and 30 ppm) and Ni (81 and 28 ppm) in the siltstone and chert samples,

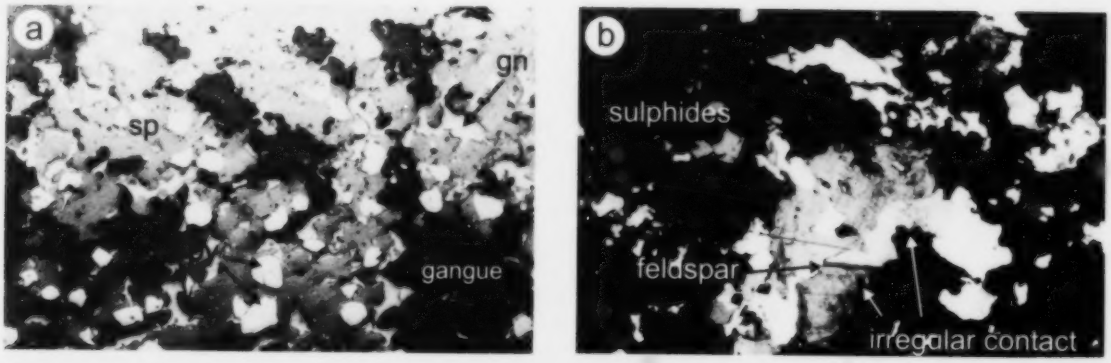


Figure 12. Sulphide textures from the A'Hearn Brook sulphide lens: (a) photomicrograph of sulphides collected from trench sample URN 120-19. See Figure 3 for sample location. (field of view is 1.3 mm, reflected light); (b) same sample as (a) except under transmitted light. Note fresh feldspar with embayed contacts adjacent to sulphides (opaque). Abbreviations: gn–galena; py–pyrite; sp–sphalerite.

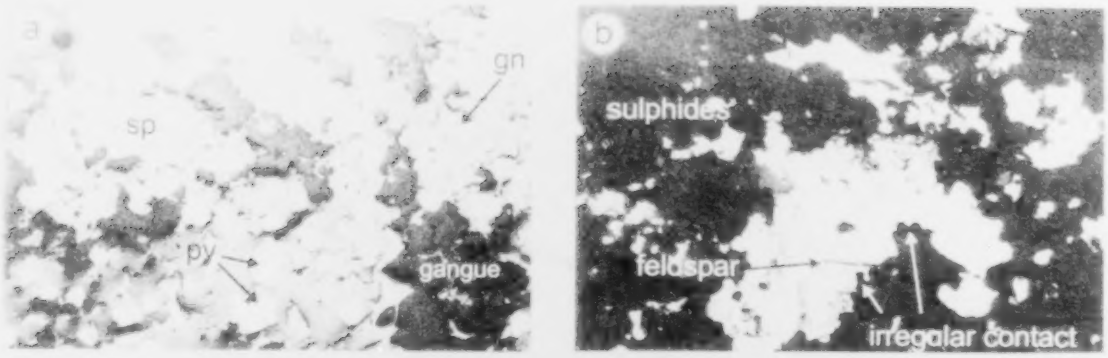
respectively, also supports a dominantly hydrogenous rather than a hydrothermal source for these rocks (Mills *et al.* 2001). However, they also contain elevated levels of Sb, W, and As relative to the other sedimentary rocks (Table 1). Most interesting is the Au content of the red chert sample (165 ppb), which is eight times that of the next closest sample in the data set.

Massive sulphides

Early reports on the A'Hearn Brook deposit describe two narrow subparallel horizons of massive sulphides. One narrow zone (< 1 m) is of higher grade and another is a wider zone (2–5 m) of lower grade (MacKenzie 1981a, 1981b, 1982, 1983). Examination of core drilled by Slam Exploration Ltd. has revealed only one mineralized horizon. However, these are shallow holes and collared too far to the west to intersect the second zone shown in Figure 4. The following discussion on massive sulphides is based solely on data collected from the Slam drill cores and one trench exposure. The main zone crops out beneath 1–2 m of till and is located immediately east of A'Hearn Brook. The same horizon was intersected in drilling approximately 480 m to the south (Figure 3). Only five drill holes have tested the interval between these two zones.

The massive sulphide lens is narrow, rarely exceeding 1 m in true thickness, and has a strike that is subparallel to stratigraphy. It crops out at surface over a strike length of at least 30 m and has been intersected at depths up to 544 m below surface (Beaumont-Smith 1995). In many of the drill sections examined, the upper and lower contacts of the massive sulphide lens are sharp, and in some instances marked by the development of bull quartz. Numerous white to buff coloured fragments of variably altered felsic volcanic material, as well as some isolated feldspar crystals, occur within the massive sulphides. The majority of the rock fragments have a well-developed schistose fabric, whereas the sulphides seem to lack a penetrative fabric.

Petrographic examination shows that the sulphides are dominantly sphalerite and pyrite with lesser amounts of galena and chalcopyrite. Paragenesis is complex and variable. In general, small grains of subrounded to rounded pyrite are overgrown by sphalerite (the predominant sulphide phase), and lesser amounts of galena and chalcopyrite (Figure 12a). Galena and less commonly chalcopyrite occur along sphalerite–sphalerite and sphalerite–pyrite grain boundaries. Small inclusions of chalcopyrite (i.e., "chalcopyrite disease") are within the sphalerite grains. Commonly,



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inclusions of a given sulphide phase may be found within other sulphide phases, such that a paragenetic order of mineralization is not readily discernable.

The lens is commonly massive but is laminated locally and, in places, contains masses of quartz as well as large, very fresh laths of alkali feldspar (?).The occurrence of undeformed and unaltered feldspar crystals within massive sulphide bodies is atypical of Bathurst Mining Camp ores. Although there is very little evidence of hydrothermal alteration of the feldspar (i.e., formation of sericite), many of the quartz and feldspar grains have irregular and embayed margins indicating a possible chemical disequilibrium with the enveloping sulphides (Figure 12b). Aggregates of quartz grains commonly display triple point grain junctions and, less commonly, undulatory extinction, indicating that they have undergone some strain.

The sulphide lens has yielded some very high grades compared to other Bathurst Minng Camp deposits. Of the four grab-sample assays presented in Table 1, the best is 32.5 wt. % Zn, 22.7 wt. % Pb and 1.6 wt. % Cu. The average Pb:Cu:Zn ratio based on these four samples is 10:1:27. However, the average grade of the lens, based on 268 assays, is 3.0 wt. % Zn, 1.77 wt. % Pb and 0.22 wt. % Cu. These base-metal ratios fall within the Zn–Pb category (Figure 13b) of volcanogenic massive sulphide deposits described by Franklin *et al.* (1981). Lithogeochemical analysis of one sample of massive sulphide collected during this study and three samples collected by McClenaghan (2002) are presented in Table1. Trace-metal analyses reveal elevated Bi (< 100 ppm), Cd (600–900 ppm), In (10–30 ppm), Sn (5–30 ppm), As (10–160 ppm), Ag (110–327 ppm), and Au (≤ 490 ppb), all within the range of typical Bathurst Mining Camp sulphide samples. The rare-earth-element data for four massive sulphide samples collected from the A'Hearn Brook deposit are presented in Figure 13a. These samples are all moderately enriched in light-rare-earth-elements relative to heavy-rare-earth elements, and have flat to slightly positive Eu anomalies, indicating that they were probably derived from moderate- to high-temperature acidic vent fluids, similar to other Bathurst Mining Camp deposits (Graf 1977).

Assay data from all reported drill-hole intercepts are plotted on the Pb–Cu–Zn ternary diagram (Figure 13b). Each point represents the assay for the total intersection. Most of the data points fall in the Zn–Pb field of Franklin *et al.* (1981), which is also typical for Bathurst Mining Camp deposits.

Hydrothermal alteration

Many of the better known Bathurst Mining Camp deposits (e.g., Halfmile Lake (Adair 1992) and Brunswick No. 12 (Lentz and Goodfellow 1994)) show evidence of significant hydrothermal alteration (distal sericite and proximal chlorite alteration) in the footwall and, to a lesser extent, in the hanging wall.

Previous workers on the A'Hearn deposit have commonly referred to chloritic alteration. Interestingly, no significant chlorite alteration was found in the Slam drill holes. In fact, feldspar crystals in the crystal tuffs hosting the deposit are largely unaffected by chlorite alteration but they are variably altered to sericite, as evidenced by the very high K_2O contents in some of these rocks (Figure 8).

As discussed in the section on major element chemistry, the crystal tuff and rhyolite samples differ in their K_2O contents. However, their respective trace-element data suggest that, with the possible exception of the andesites, they are sourced from the same magma. If this is true, then the variability in alkali-element content suggests that hydrothermal alteration and/or regional metamorphism mobilized the alkali elements.

Hydrothermal alteration in volcanic sequences is best demonstrated by mass balance analysis. In the case of Flat Landing Brook felsic volcanic rocks, normalization to the average unaltered Flat

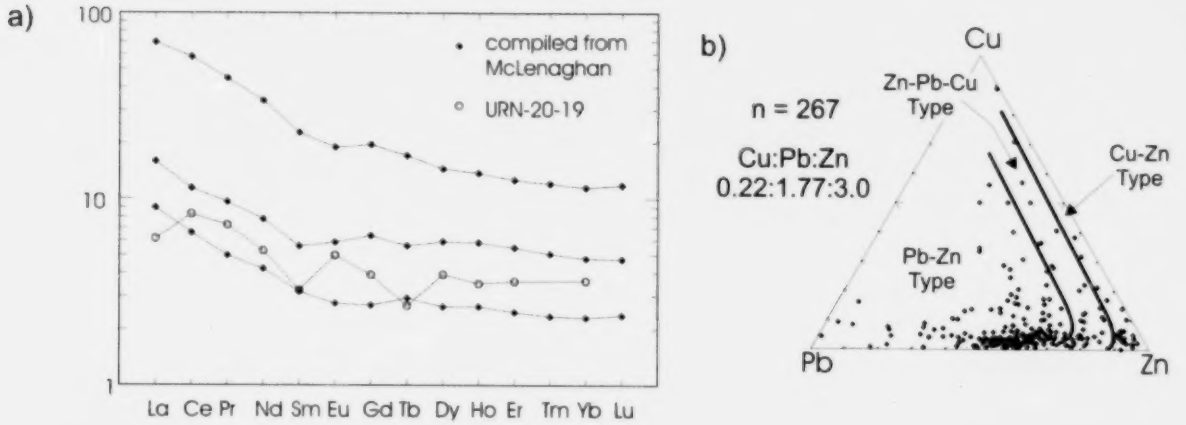

Figure 13. Sulphide geochemistry of the A'Hearn Brook deposit: (a) Pb–Cu–Zn ternary diagram (modified from Franklin *et al.* 1981) for assay data from the A'Hearn Brook deposit. Data compiled from assessment reports listed in section on Previous Work; (b) chondrite-normalized rare-earth-element profiles for A'Hearn Brook sulphide sample collected during this study, and for three samples compiled from McClenaghan (2002). Normalization factors are from Evensen (1978).

Landing Brook rhyolite was conducted according to methods outlined in Barrett and MacLean (1994), assuming TiO_2 to be immobile.

A plot of mass-corrected Fe_2O_3 + MgO versus SiO_2 (Figure 14a) shows that most of the crystal tuff and ash tuff samples have undergone mass gain of between 0.5 and 5% (Fe_2O_3 + MgO) and variable addition or loss of SiO_2, whereas most of the rhyolite samples are depleted in Fe_2O_3 + MgO. A similar plot of Na_2O + K_2O versus SiO_2 shows that most samples of felsic volcanic rock have undergone a net mass loss in Na_2O + K_2O of between 1 and 5% with an accompanying loss in SiO_2 of between 0 and 50% (Figure 14b). Mass loss in alkali elements is typical of low-temperature hydrothermal alteration where seawater is the dominant fluid.

DISCUSSION

The mode of formation of the A'Hearn Brook sulphide body is problematic, with several hypotheses possible, e.g., stratiform exhalative, subsurface replacement, remobilization of an existing volcanogenic massive sulphide body, or magmatic sulphide vein. The following five observations / points are salient to possible interpretations:

1. The contacts between the massive sulphide lens and the host rocks are sharp.

2. There are numerous examples of disequilibrium in the sulphide body, e.g., rounded pyrite grains, unaltered embayed albite and quartz crystals, etc.

3. Highly sericite-altered host rocks occur as clasts within the sulphide body along with unaltered albite crystals, suggesting that the wall rock and sulphide body have not undergone the same deformation–alteration history.

4. The presence of sulphides immediately above tholeiitic rocks is interesting in that the transition from intermediate to tholeiitic volcanism usually implies an increase in the thermal gradient.

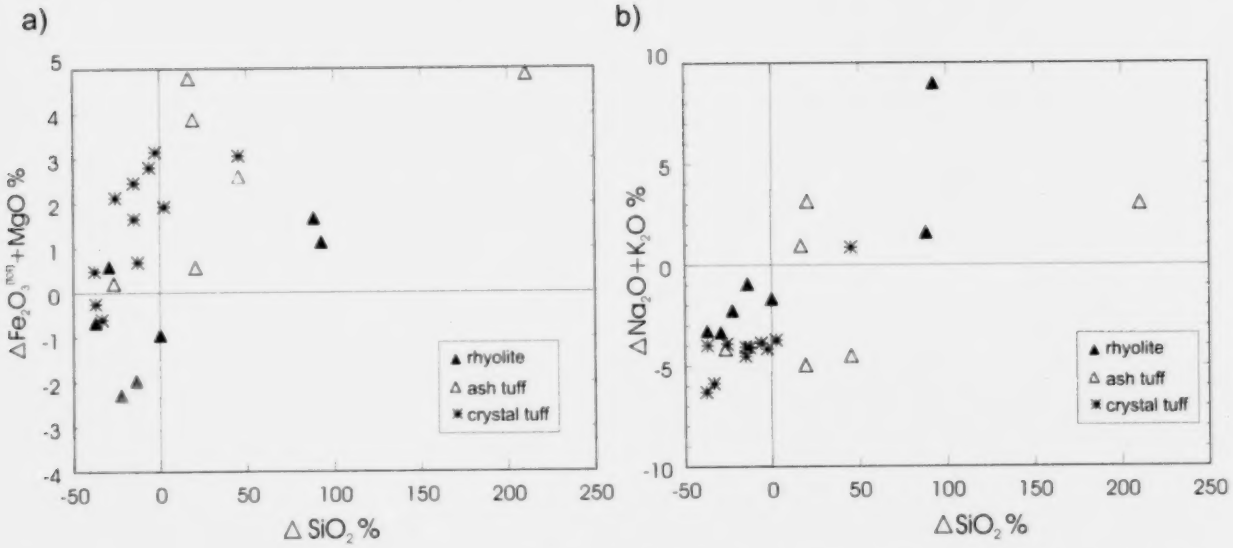

Figure 14. Mass recalculated data for felsic volcanic rocks from the A'Hearn Brook deposit: (a) Fe_2O_3 + MgO versus SiO_2; (b) $Na_2O + K_2O$ versus SiO_2. Uncorrected data is presented in Table 1.

5. The sulphide lens is in direct contact with hydrogenous manganiferous sedimentary rocks to the west implying that growth of the sulphide deposit may have been terminated by transition to an oxic water column.

These observations permit at least three possible interpretations regarding the mode of emplacement of the A'Hearn Brook sulphide body, namely:

1. Emplacement of the A'Hearn Brook sulphide body was synchronous with deposition of the lower part of Roger Brook Member (Flat Landing Brook Formation), immediately prior to the seawater column becoming oxic. The absence of vent facies stringer zone mineralization and/or significant footwall alteration implies that stratiform sulphide accumulation occurred at a location distal to the vent complex, or possibly as a subsurface replacement. The mineralizing fluids continued to vent in to the water column after the switch to oxic conditions, as evidenced by elevated Cd, In, Sn, Ag, Au, and As contents in red chert and shale from the hanging wall.

2. A second interpretation invokes some sort of a felsic intrusion-related vein system. However, this interpretation is considered less likely because of the limited number of phases present in the "vein", and the absence of zoning. A vein-type system would be expected to display hydrothermal alteration envelopes symmetrically arranged about the vein. There is no evidence at A'Hearn Brook for this type of alteration.

3. The third and most likely interpretation invokes a remobilization of an earlier-formed volcanogenic massive sulphide deposit via dynamic deformation/metamorphic processes. This is the most logical interpretation as it explains both the atypical sulphide textures and the very low aspect ratio of the sulphide body, as well as the apparent lack of hydrothermal alteration.

The occurrence of very fresh albitic feldspar crystals within the sulphide body is atypical for Bathurst Mining Camp deposits, and must be related to either metamorphic or remobilization

processes because the pressure–temperature–compositional conditions in a volcanogenic massive sulphide system would destroy any alkali feldspar. However, the rare-earth-element chemistry of the A'Hearn Brook massive sulphides, in particular the light-rare-earth-element enrichment and flat Eu profiles are consistent with volcanogenic massive sulphide deposition from a moderately hot, dominantly seawater-sourced mineralizing fluid, providing additional support for the third interpretation given above.

CONCLUSIONS

The A'Hearn Brook deposit is tentatively placed in the Flat Landing Brook Formation near the base of the Roger Brook Member. Mineralization was synchronous with felsic volcanism as evidenced by embayed albite and quartz crystals in the massive sulphides. Black shale in the footwall and immediate hanging wall support anoxic conditions at the site of deposition, whereas the occurrence of red shale and chert with elevated Mn contents and positive Ce anomalies slightly higher in the hanging wall are indicative of a transition to an oxygenated water column. The presence of elevated Sb, W. As, and Ag contents in the oxidized facies suggests that hydrothermal activity continued after the transition to oxic seawater conditions.

The deposit most likely originated as a stratiform exhalative sulphide body. Subsequent deformation and remobilization of the sulphide body during thrusting is invoked as the mechanism responsible for atypical sulphide textures (i.e., rounded pyrite grains and sphalerite ± galena) in the massive lens. Remobilization may also explain the emplacement of the "unaltered" sulphide body into the sericite-altered host sequence.

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STRATIGRAPHY, EVAPORITE STRUCTURE AND TECTONIC HISTORY IN THE MCCULLY AREA, SOUTHERN NEW BRUNSWICK: PRELIMINARY RESULTS †

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WILSON, P. 2003. Stratigraphy, evaporite structure and tectonic history in the McCully area, southern New Brunswick: preliminary results. *In* Current Research 2002. *Edited by* B.M.W. Carroll. New Brunswick Department of Natural Resources; Minerals, Policy and Planning Division, Mineral Resource Report 2003-4, pp. 101–121.

The McCully gas field is located in the western part of the Late Devonian–Carboniferous Moncton Subbasin, immediately to the northeast of the town of Sussex. The area is of economic importance because of the presence of potash deposits in the Viséan Cassidy Lake Formation (Windsor Group) and the presence of a petroleum system in the Tournaisian Albert Formation (Horton Group). However, the stratigraphy, structural geology and tectonic history of the area are incompletely understood. A structural study of this area incorporating field, borehole and seismic data is currently being undertaken by the author. The aim of the study is to understand the structural geology and three-dimensional architecture of the study area, with emphasis on the morphology, kinematics and timing of faults. The implications for emplacement and structural control of potash and rock salt deposits, and the structural control of the petroleum system in the study area are emphasized.

New seismic, borehole and field evidence suggests that revisions to the pre-Windsor stratigraphy of the basin are required. Pre-Windsor strata are divided into two groups, the lower Horton Group and the upper Sussex Group. The structural geology of evaporite deposits in the area is complex, with internal and basal dislocations and isoclinal folding accommodating southeast-directed thrusting that is localized into the evaporite body. Halotectonism in the area is related to a late (probably latest Carboniferous or Permian) contractional event that also caused reverse movements on major northeast-trending fault systems.

Le champ de gaz de McCully est situé dans la partie occidentale du sous-bassin du Dévonien tardif–Carbonifère de Moncton, immédiatement au nord-est de la ville de Sussex. Les lieux présentent une importance économique en raison de la présence de gîtes de potasse dans la Formation viséenne de Cassidy Lake (groupe de Windsor) ainsi que d'un système pétrolifère dans la Formation tournaisienne d'Albert (groupe de Horton). On ne comprend toutefois pas entièrement la stratigraphie, la géologie structurale et le passé tectonique du secteur. L'auteur est présentement en train de réaliser une étude structurale de ce secteur incorporant des données de terrain, des données de forage et des données sismiques. L'étude vise à comprendre la géologie structurale et l'architecture tridimensionnelle du secteur d'étude en accordant un accent particulier sur la morphologie, la cinétique et le moment de la formation des failles. L'étude s'attarde surtout sur les répercussions de la mise en place et du contrôle structural des gîtes de potasse et de sel gemme, ainsi que sur le contrôle structural du système pétrolifère du secteur d'étude.

De nouvelles observations sismiques, de forage et de terrain permettent de supposer que des modifications s'avèrent nécessaires à la stratigraphie du bassin préalable au groupe de Windsor. Les strates pré-Windsor se subdivisent en deux groupes : le groupe inférieur de Horton et le groupe supérieur de Sussex. La géologie structurale des gîtes d'évaporites du secteur est complexe, avec des dislocations internes et basales et un plissement isoclinal permettant un chevauchement orienté vers le sud-est, localisé à l'intérieur de la masse d'évaporites. Le halotectonisme dans le secteur est apparenté à un phénomène de contraction qui a également entraîné des déplacements inverses sur les principaux systèmes de failles orientées vers le nord-est.

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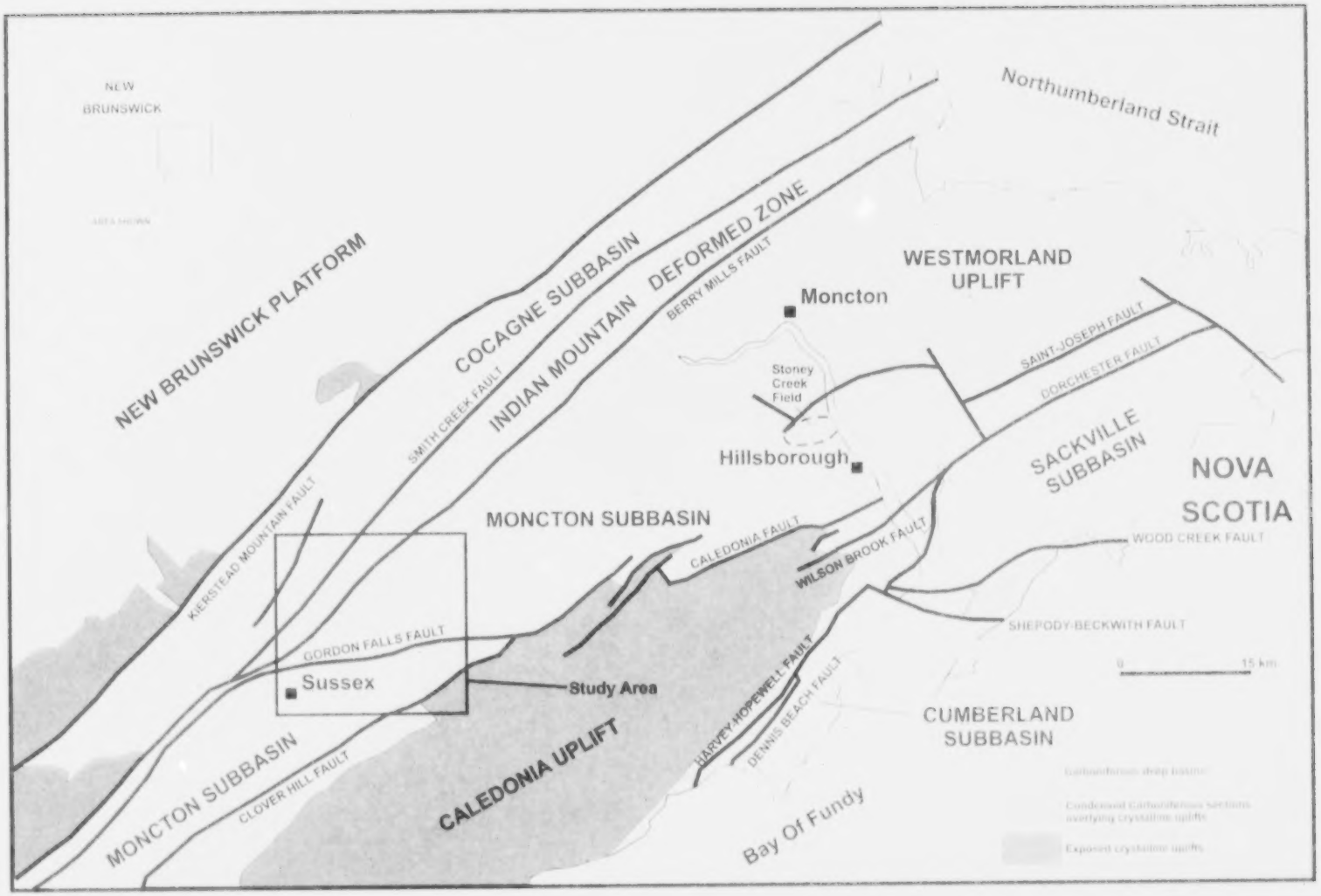

Figure 1 Regional map of the Maritimes Basin in southeastern New Brunswick, showing the major faults. Redrawn after St. Peter (2001).

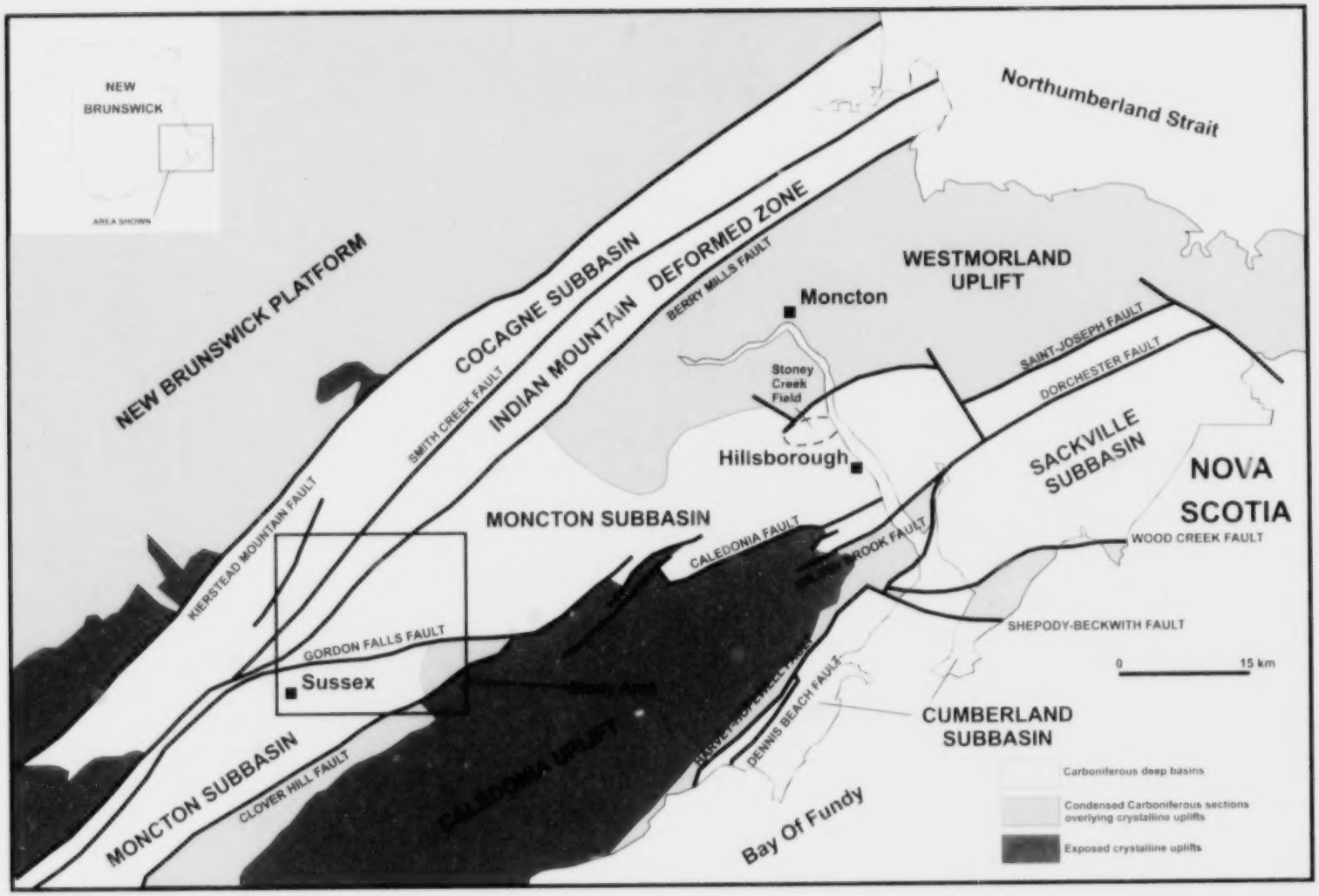

Figure1. Regional map of the Maritimes Basin in southeastern New Brunswick, showing the major faults. Redrawn after St. Peter (2001).

INTRODUCTION

Objective

The primary objective of this study is to understand the structural geology and three-dimensional architecture of the Late Devonian–Carboniferous rocks within the Moncton Subbasin to the northeast of Sussex, New Brunswick. Special attention is paid to the morphology, kinematics and timing of structures relevant to the emplacement and control of potash deposits in the study area, and to structural control of the petroleum system in Albert Formation rocks of the McCully gas field. It is envisaged that an integrated study of surface exposures, industry and public domain seismic reflection data, drill core data from potash exploration holes and well cuttings from the McCully gas field will allow the stratigraphy and structural geology of this area to be advanced, leading to the determination of structural controls on (1) sedimentation, (2) hydrocarbon traps, and (3) potash and salt emplacement in the study area. The applicability of the data to the larger Maritimes Basin will be assessed.

Background

The Moncton Subbasin is a substructure of the Upper Palaeozoic Maritimes Basin, a post-Acadian successor basin that underlies much of the Maritime Provinces and Gulf of St. Lawrence. The distribution of Upper Devonian and Carboniferous rocks of the Maritimes Basin in southeastern New Brunswick is shown in Figure 1. The study area is immediately to the north and east of the town of Sussex (Figure 1). A geological map of the study area is given in Figure 2.

Hydrocarbon exploitation in the Moncton Subbasin of New Brunswick has had a long history. According to St. Peter (2001), around 800,000 barrels of paraffinic oil and 30,000,000,000 ft^3 of sweet gas were produced from the Stoney Creek field (approximately 15 km south of Moncton, Figure 1) between the years of 1910 and 1991, when the field ceased production. More recent hydrocarbon exploration in the Moncton Subbasin has concentrated on the Hillsborough area (straddling the Petitcodiac River approximately 25 km south of Moncton; Wilson 2002) and the McCully gas field near Sussex, New Brunswick, which is the field area for this study. Potash deposits have also been worked in the study area. The Potash Corporation of Saskatchewan Inc. (PCS) potash and rock salt mine at Penobsquis opened in 1983, and PCS initiated a new potash exploration program in the study area in 2002.

The tectonic evolution of the Moncton Subbasin has involved numerous periods of movement on northeast- to east-trending basin-controlling faults. Strike-slip movements have been important on at least some of these faults (Bradley 1982; Mosher and Rast 1984; Nance and Warner 1986; Nance 1987; Foley 1989; St. Peter 1992, 1993; Nickerson 1994; Wilson 2002). Halotectonism has contributed to deformation in some parts of the Maritimes Basin, including the area of this study. The protracted and complex tectonic history of the basin has led to rapid internal facies variations within some of the basin rock units, notably the lacustrine hydrocarbon-bearing Albert Formation (Greiner 1962, 1974; Macauley *et al.* 1984; Carter and Pickerill 1985a, 1985b; St. Peter 1992, 1993; van de Poll 1995). This, coupled with the generally poor exposure and complex structural geology of the area, has hindered a clear understanding of the structural and tectonic history of the area and, in particular, the identification of new hydrocarbon prospects in the Moncton Subbasin.

Methods

Selected field transects were undertaken in the map area during the 2002 field season, especially in the southeast (Urney and Cedar Camp areas; Figure 2) where structure is complex and exposure reasonably good. Cores from mineral exploration boreholes drilled in the study area were examined,

45°52'00" N
65°32'00" W
Berry Mills Fault
L6
L5
L2
L4
Smiths Creek
PCS-02-05
PCS-02-03
SUSSEX
Sussex Corner
Picadilly
Urney
Dutch Valley
Mill Brook
Cedar Camp Brook
65°32'00" W
45°41'00" N

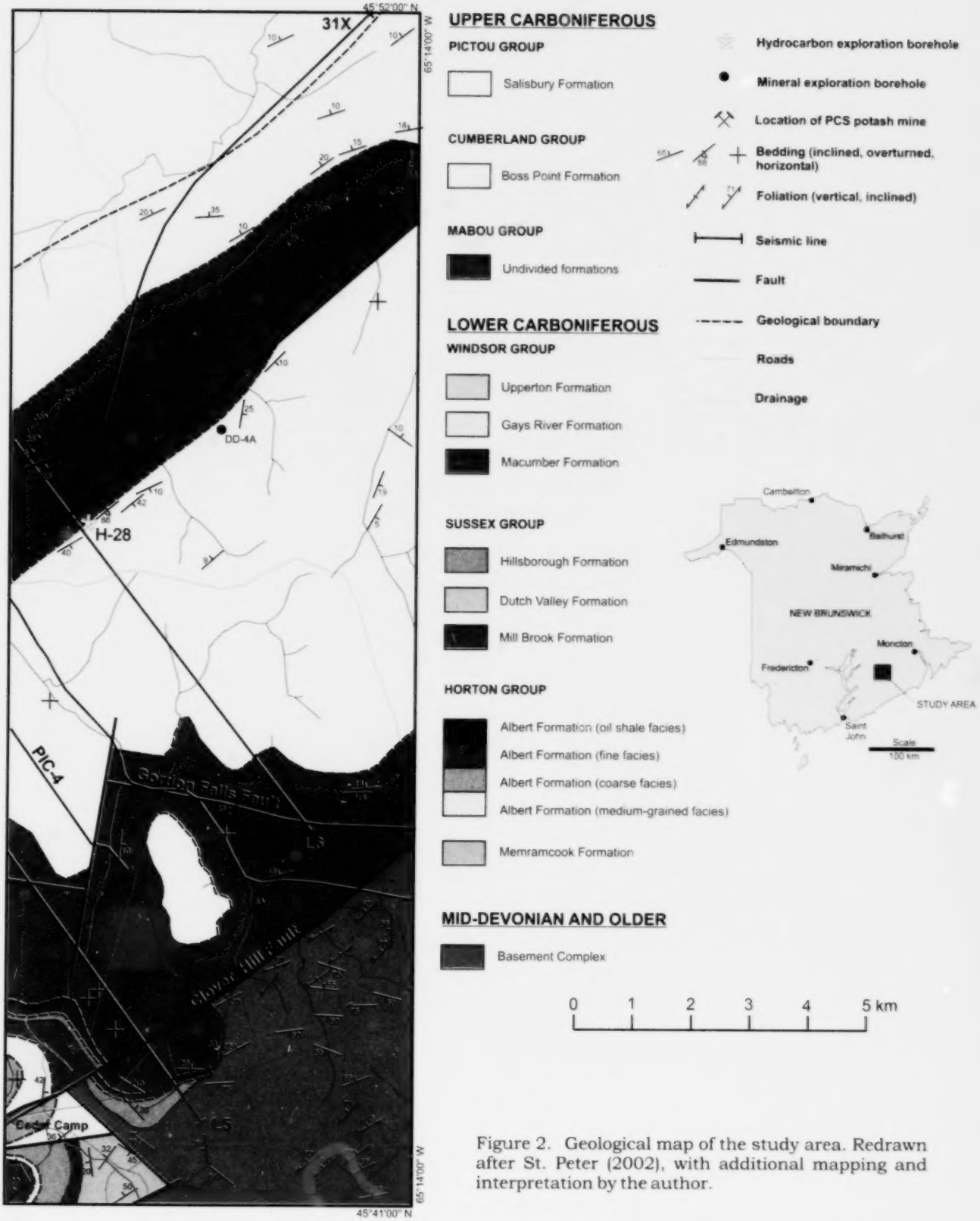

Figure 2. Geological map of the study area. Redrawn after St. Peter (2002), with additional mapping and interpretation by the author.

Jordan Mountain
Burry Mills Fault
L6
L5
L2
Smiths Creek
D-48
34Y
Z-4
K-5
K-3
V-4
Penobsquis #1
L3
S-4
L4
L1
McCully 1/2
P-4
M-4A
N-3
P-56
N-2
P-1
J-4A
K-4
K-5A
H-5
L-4
J-3
K-2
G-4A
G-3A
F-4A
PCS-02-05
H-3
F-3A
H-4A
J-65
C-4
E-3
D-3
E-2A
Plumweep #1
PIC-2
PIC-3
Kerr-McGee Urney #1
Gordon Falls Fault
D-2A
PCS-02-04
B-3
31X
C-75
PCS-02-01
PIC-1
L2
L1
SUSSEX
L3
Urney
Sussex Corner
Picadilly
Urney Fault
Ditch Valley
L4

UPPER CARBONIFEROUS

PICTOU GROUP

CUMBERLAND GROUP

MABOU GROUP

LOWER CARBONIFEROUS

WINDSOR GROUP

SUSSEX GROUP

HORTON GROUP

MID-DEVONIAN AND OLDER

Table 1. Table of Formations for the Western Moncton Subbasin.

STAGE	SYSTEM		GROUP	FORMATION	LITHOLOGY
UPPER CARBONIFEROUS	WESTPHALIAN	D	PICTOU		
		C		SALISBURY	Red mudstone, siltstone, sandstone and conglomerate; minor thin coal seams
		B			
		A	CUMBERLAND	BOSS POINT	Yellow–grey quartzose sandstone and quartz-pebble conglomerate; minor red sandstone, grey and red mudstone, thin coal seams
	NAMURIAN	C			
		B			
		A			
LOWER CARBONIFEROUS	VISÉAN		MABOU	UNDIVIDED UNITS	Red to grey polymictic pebble and cobble conglomerate; minor red sandstone
			WINDSOR	CLOVER HILL	Halite, argillaceous halite, anhydrite and claystone
				CASSIDY LAKE	Halite, argillaceous halite, sylvinite and anhydrite
				UPPERTON	Anhydrite and gypsum
				MACUMBER/ GAYS RIVER	Wackestone, packstone, algal boundstone; minor floatstone and intraformational breccia
	TOURNAISIAN		SUSSEX	HILLSBOROUGH	Yellow–grey to red polymictic conglomerate and sandstone; minor red mudstone
				DUTCH VALLEY	Red mudstone, siltstone and fine sandstone; minor grit and polymictic conglomerate
				MILL BROOK / HAZEL HILL MEMBER	Grey polymictic conglomerate, grit and coarse sandstone HAZEL HILL: Grey conglomerate containing green–grey chert and marble clasts
			HORTON	WELDON	Red mudstone, siltstone and fine sandstone; minor grit and polymictic conglomerate
				ALBERT	Mostly grey feldspathic sandstone, mudstone, kerogeneous mudstone and shale, polymictic conglomerate; minor limestone
				MEMRAMCOOK	Red to grey polymictic boulder conglomerate with minor sandstone and mudstone
UPPER DEVONIAN					
MID. DEVONIAN AND OLDER			BASEMENT COMPLEX		

and the structural features therein recorded. Of these boreholes, thirty were drilled by the Potash Company of America (PCA) in the middle to late 1970s, and a further five were drilled by PCS in 2002. The locations of the boreholes are shown in Figure 2. Industry-generated seismic reflection profiles provided by PCS and Corridor Resources Inc. were interpreted. Six new seismic reflection profiles and two reprocessed public-domain seismic reflection profiles were provided by Corridor Resources Inc. Four additional profiles acquired by PCS for potash exploration were also provided. All seismic profiles were converted from two-way time to depth. The profiles form a grid, with ten northwest–southeast-trending profiles and two northeast–southwest-trending profiles. The locations of the profiles are shown in Figure 2. Borehole control is provided by PCS/Corridor McCully 1 and 2, Corridor/PCS McCully P-56 and C-75, and EOG/Corridor McCully D-48, H-28 and J-65, all of which were completed in the Albert Formation. The locations of these boreholes are shown in Figure 2. Additional control on evaporite stratigraphy and structure is provided by PCA and PCS mineral exploration coreholes. A review of the pertinent literature, published maps, and available core, cuttings and wireline logs is also in progress.

LITHOSTRATIGRAPHY

The Horton Group in the Moncton Subbasin has been traditionally divided into three conformable formations; in ascending order, the Memramcook, Albert, and Weldon formations (Table 1). These formations are unconformably overlain by polymictic conglomerate of the Hillsborough Formation. Earlier workers (e.g., Norman 1941a, 1941b; Gussow 1953) included the Hillsborough and Weldon formations as part of the Moncton Group, a unit which in their definition straddles the Horton/Windsor boundary (see Figure 2 of Gussow 1953). However, Carter and Pickerill (1985b) noted that this scheme contravenes the stratigraphic code, and recommended that the Weldon and Hillsborough be reduced to member status within the Moncton Formation, and that the Horton/Windsor boundary be placed at the base of the first marine bed (i.e., above the Hillsborough Formation), as in the original definition of those groups (Bell 1929). More recent schemes (St. Peter 1992, 1993; 2001) have placed the Hillsborough Formation at the base of the Windsor Group, and the Weldon Formation at the top of Horton Group, abandoning the name Moncton entirely.

The Weldon Formation is traditionally defined as conformably overlying the Albert Formation (Norman 1941a, 1941b; Gussow 1953; St. Peter 1992, 1993). Gussow (1953) described the contact as being "in general, conformable and gradational with the overlying Moncton Group [i.e., his Weldon Formation], the gradation being accomplished through a fairly thin transition zone of interbedded red and grey beds." St. Peter (1992) noted two localities where the Albert/Weldon contact is exposed, and a further four localities where the units are separated by only a narrow concealed interval, concluding that the contact is conformable. He also noted that seismic profiles in the Moncton Subbasin showed no angular discordance between Albert and Weldon formations. Although interpretations of reprocessed seismic reflection profiles from the Hillsborough area by Lynch (1999) suggested an Albert/Weldon unconformity, Wilson (2002) considered that Lynch's interpretations were only in part supported by field and borehole evidence. Reinterpretations (Wilson 2002) show the contact as conformable. The contact between the Weldon and the overlying Hillsborough Formation is more problematic, having been described as conformable in some areas (e.g., near Sussex) and as a pronounced angular unconformity in others , e.g., Hillsborough (Gussow 1953; Carter and Pickerill 1985b; van de Poll 1995). Mapping in the Hillsborough area clearly shows a pronounced angular unconformity between highly faulted and deformed Albert and Weldon rocks and the less-deformed overlying Hillsborough Formation (e.g., St. Peter and Johnson 1997).

With new mapping and the availability of new industry-generated seismic reflection profiles in the Sussex area, it is clear that pre-Windsor stratigraphic revisions are required. In the study area, the Weldon Formation has previously been defined to include a basal grey conglomerate unit (coarse facies) and an upper fine-grained redbed unit (fine facies) (St. Peter 2002). However, seismic reflection profiles clearly show that these units overlie the Albert Formation with angular

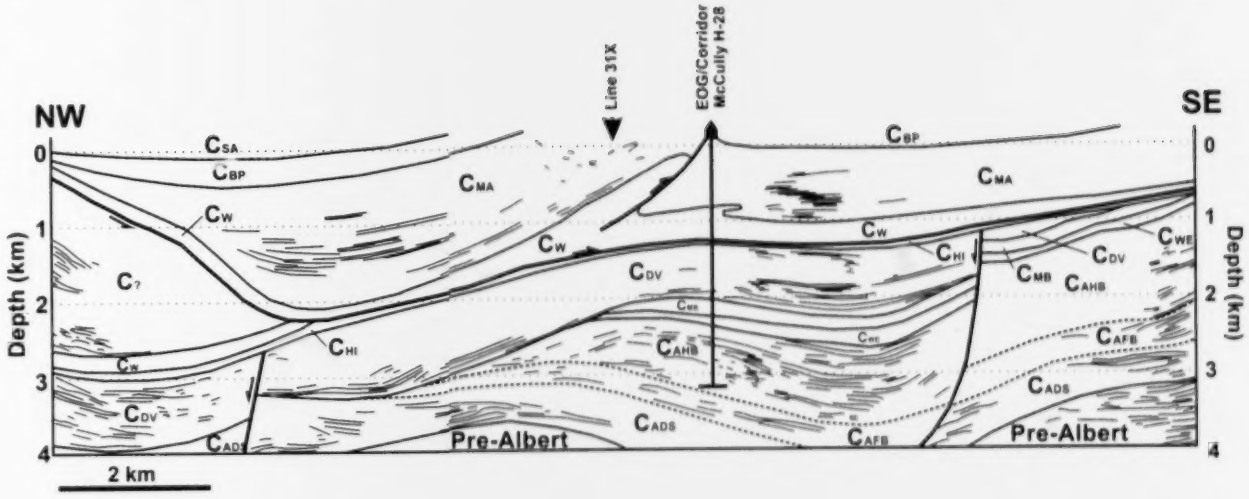

Figure 3. Interpretation of Seismic line 6 (L6 on Figure 2). Rock units: CSA – Salisbury Formation; CBP – Boss Point Formation; CMA – Mabou Group; CW – Windsor Group; CHI – Hillsborough Formation; CDV – Dutch Valley Formation; CMB – Mill Brook Formation; CWE – Weldon Formation; CAHB – Albert Formation (Hiram Brook Member); CAFB – Albert Formation (Frederick Brook Member); CADS – Albert Formation (Dawson Settlement Member). C? – unknown (see section "Fault Kinematics and Tectonic History"). Borehole control is provided by EOG/Corridor McCully H-28.

unconformity, and that they are overlain with apparent structural conformity by the Hillsborough Formation. In the H-28 borehole (Figures 2 and 3), Albert Formation rocks are conformably overlain by approximately 100 m of red claystone, shale, siltstone and fine sandstone. This redbed unit conformably overlies the Albert Formation and, therefore, conforms to the original definition of the Weldon Formation. In turn, the redbed unit is overlain by the polymictic conglomerates and fine-grained redbeds that were previously assigned to the Weldon Formation. The interpretation of Line 2 (Figure 4) shows that Horton Group rocks are unconformably overlain by a section of polymictic conglomerate that, in turn, is overlain by fine-grained redbeds. Previously, this section would have been assigned to the Weldon Formation. In fact, the section is significantly younger than the Weldon Formation, and the units within the section require new names.

To resolve these difficulties, the name Weldon is retained for the lower redbed unit that rests conformably upon the Albert Formation, since this unit holds an analogous position to the Weldon Formation in the type locality of Weldon Creek, near Hillsborough. The name Mill Brook Formation has been assigned to the grey and red conglomerate unit that overlies the major post-Weldon unconformity (Figure 2; St. Peter 2002). The name Dutch Valley Formation has been assigned to the thick unit of fine-grained redbeds that overlies the Mill Brook Formation (Figure 2; St. Peter 2002).

Since the presence of an unconformity has tectonic significance, which should be reflected in any stratigraphic framework, it is suggested that the rock units below the Windsor marine beds should be divided into two groups: a lower Horton Group consisting of the Memramcook, Albert and Weldon formations and an upper Sussex Group consisting of the Mill Brook, Dutch Valley and Hillsborough formations (Figure 2; Table 1). Accordingly, the Weldon/Hillsborough contact is defined as everywhere unconformable, while the contact between the Dutch Valley and Hillsborough formations is everywhere structurally conformable.

The threefold division of the Sussex Group as seen in the study area is not observed in the Hillsborough area, in the eastern part of the Moncton Subbasin (Figure 1). This is thought to be because the surface exposures of the Sussex Group section in the Hillsborough area are proximal to the source rocks of the Caledonia Massif and the entire section is coarse. Therefore, the section is assigned to the Hillsborough Formation (St. Peter, personal communication 2003).

Each stratigraphic unit in the study area is briefly described below.

Basement complex

Rocks of the basement complex outcrop to the southeast of the Clover Hill Fault (Figures 1 and 2), and in the fault-bounded Jordan Mountain uplift in the northwest of the study area (Figure 2). The basement complex consists of Proterozoic to Middle Devonian metasediments, metavolcanics and igneous rocks which underlie the Late Devonian–Carboniferous sedimentary rocks of the Maritimes Basin. Basement rocks in southern New Brunswick are assigned to the Avalon Zone of the Appalachian orogen (Williams 1979). More recently, workers have divided the Avalon Zone into several terranes (e.g., Barr and White 1996, and references therein).

Horton Group

The Horton Group is the basal stratigraphic group of the Moncton Subbasin. It consists of the conformable Memramcook, Albert and Weldon formations.

The Memramcook Formation is exposed in fault-bounded blocks in the southeast and northwest of the study area. It consists of purple–red polymictic conglomerates with hematite-coated clasts, arkosic sandstones and minor red mudstones. It is late Devonian in age and is overlain by the earliest Carboniferous Albert Formation. It contains Late Devonian miospores in the type section at Stoney Creek, southeast of Moncton (Carr 1968).

The Early to Middle Tournaisian Albert Formation is economically important because it contains a petroleum system in the study area. The Albert Formation consists of five members which have complex interdigitating relationships (e.g., Greiner 1974; Macauley *et al.* 1984; Carter and Pickerill 1985a, 1985b; van de Poll 1995). The distal basin-centre facies comprise the Dawson Settlement, Frederick Brook, Hiram Brook and Gautreau members. The Dawson Settlement Member consists mainly of coarse to fine sandstones with intercalations of shale; the Frederick Brook Member consists of kerogeneous shale and minor sandstone; the Hiram Brook Member consists of kerogeneous and calcareous siltstones, shales and sandstones; and, in the southeastern Moncton Subbasin, the Gautreau Member (Carter and Pickerill 1985b) comprises evaporites and shales thought to represent a salt-flat facies deposited during the drying up of lake Albert (St. Peter 1992), and is laterally equivalent to the Hiram Brook member. The mainly conglomeratic Round Hill Member (Macauley *et al.* 1984; Carter and Pickerill 1985b) is thought to represent the near-source, proximal alluvial-fan facies equivalent of the distal basin facies (McLeod 1980; Carter and Pickerill 1985b; van de Poll 1995). In the area of study, only the Dawson Settlement, Frederick Brook and Hiram Brook members are present. It should be noted that, to some degree, these three members are likely to be lateral equivalents. The Albert Formation is conformably or paraconformably overlain by the Weldon Formation, and unconformably overlain by younger units.

The mid-Tournaisian Weldon Formation consists of red mudstones, siltstones and shales with minor conglomerates and limestone intercalations. The Weldon Formation has been cut out by the post-Horton unconformity over much of the study area; however, it is present in the subsurface. The Weldon Formation is unconformably overlain by rocks of the Sussex Group.

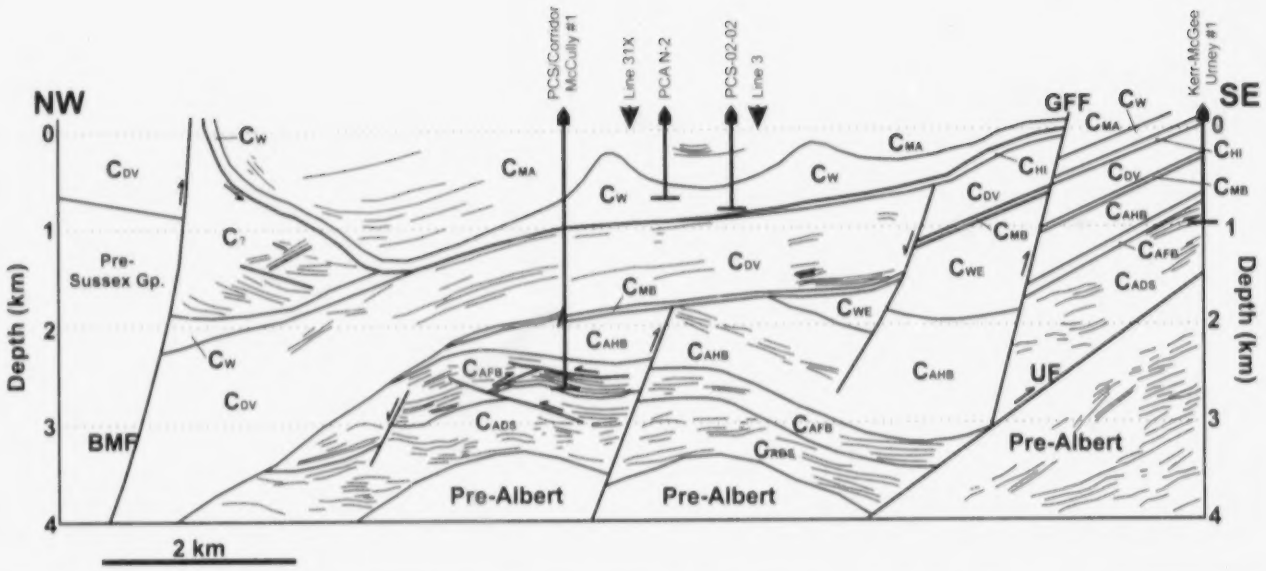

Figure 4. Interpretation of seismic line 2 (L2 on Figure 2). Rock units: CMA – Mabou Group; CW – Windsor Group; CHI – Hillsborough Formation; CDV – Dutch Valley Formation; CMB – Mill Brook Formation; CWE – Weldon Formation; CAHB – Albert Formation (Hiram Brook Member); CAFB – Albert Formation (Frederick Brook Member); CADS – Albert Formation (Dawson Settlement Member); C? – unknown (see section on "Fault Kinematics and Tectonic History"). Faults: BMF – Berry Mills Fault; GFF – Gordon Falls Fault; UF – Urney Fault. Borehole control is provided by PCS/Corridor McCully #1, PCA N-2, PCS-02-02 and Kerr-McGee Urney #1.

Sussex Group

The Sussex Group consists of the Mill Brook (including the Hazel Hill Member), Dutch Valley and Hillsborough formations. The names Sussex Group, Mill Brook Formation, Hazel Hill Member and Dutch Valley Formation are new, and have been approved by the Geological Survey of Canada (St. Peter, personal communication 2003). There may be minor unconformities between these formations, but they are generally structurally conformable.

The Mill Brook Formation outcrops principally in the south of the study area around Urney and Cedar Camp. It unconformably overlies the Weldon and Albert formations, and consists of grey–green to reddish polymictic conglomerates, lithic microconglomerates, lithic sandstones and minor mudstones. Along Highway No. 1 just west of Sussex, a distinctive chert and marble clast conglomerate can be seen unconformably overlying shales of the Albert Formation; this is the Hazel Hill Member of the Mill Brook Formation (St. Peter 1995). In seismic reflection profiles, the Mill Brook Formation has a variable thickness of 50–200 m; it is considerably thicker to the south in the type locality of Mill Brook (Figure 2; St. Peter 1995).

The Dutch Valley Formation outcrops in the south of the study area and immediately to the northwest of the Berry Mills fault. It consists mostly of red mudstone, siltstone and fine sandstone; however, grit and polymictic conglomerate are locally present. It conformably overlies the Mill Brook formation. Seismic interpretations and well intersections suggest that the unit has a thickness of around 800 m in the centre of the basin, and thins towards the Clover Hill Fault in the southeast (Figures 3 and 4).

Table 2. Internal Stratigraphy of the Windsor Group in the Western Moncton Subbasin.

GROUP	FORMATION	MEMBER		LITHOLOGY
MABOU	Undivided Units			Red to grey polymictic pebble and cobble conglomerate; red and minor green mudstone and sandstone.
WINDSOR	Clover Hill	Penobsquis Salt		Coarse crystalline, clean to argillaceous, grey to pale orange halite.
		Upper Anhydrite		Fine-grained to cryptocrystalline, dark grey–blue massive anhydrite.
	Cassidy Lake	Upper Halite	Coarse	Coarse, clean to argillaceous transparent, grey and pale orange halite.
			Finely Laminated	Red–purple argillaceous halite and sylvinite with millimetre-scale laminae of grey–green clay.
			Sylvinite	Low-grade sylvinite; carnallite in the northeast.
			Banded	Broad (10s cm) bands of coarse, clean translucent to pale orange halite, red–purple argillaceous and sylvitic halite, and sylvinite.
		Ore Zone		Sylvinite at KCl grades up to ~40%; usually associated with medium to coarse crystalline pale grey halite, traces of blue halite and disseminated grey–green or red–brown clay.
		Middle Halite	Red-brown	Red-brown argillaceous halite.
			Grey-green	Grey–green argillaceous halite.
		Basal Halite		Coarse, transparent to dark grey, clean to anhydritic halite.
	Upperton			Fine-grained to cryptocrystalline dark grey–blue massive to finely laminated anhydrite.
	Macumber			Thinly bedded to laminated, dark grey, sparsely fossiliferous limestone.
SUSSEX	Hillsborough			Yellow–grey to red polymictic conglomerate and lithic sandstone; minor red mudstone.

The Hillsborough Formation outcrops principally along a prominent ridge between Picadilly and Urney, as well as on the south side of Jordan Mountain in the northwest of the study area (Figure 2). The Hillsborough Formation consists of yellow–grey, grey or red polymictic conglomerates and coarse lithic sandstones. It overlies the Dutch Valley Formation, and is overlain with structural conformity by the marine rocks of the Windsor Group.

Windsor Group

In this part of the Moncton Subbasin, the Windsor Group consists largely of marine evaporites. A review of the Windsor Group stratigraphy was published by McCutcheon (1981) and much of the following is derived from his work.

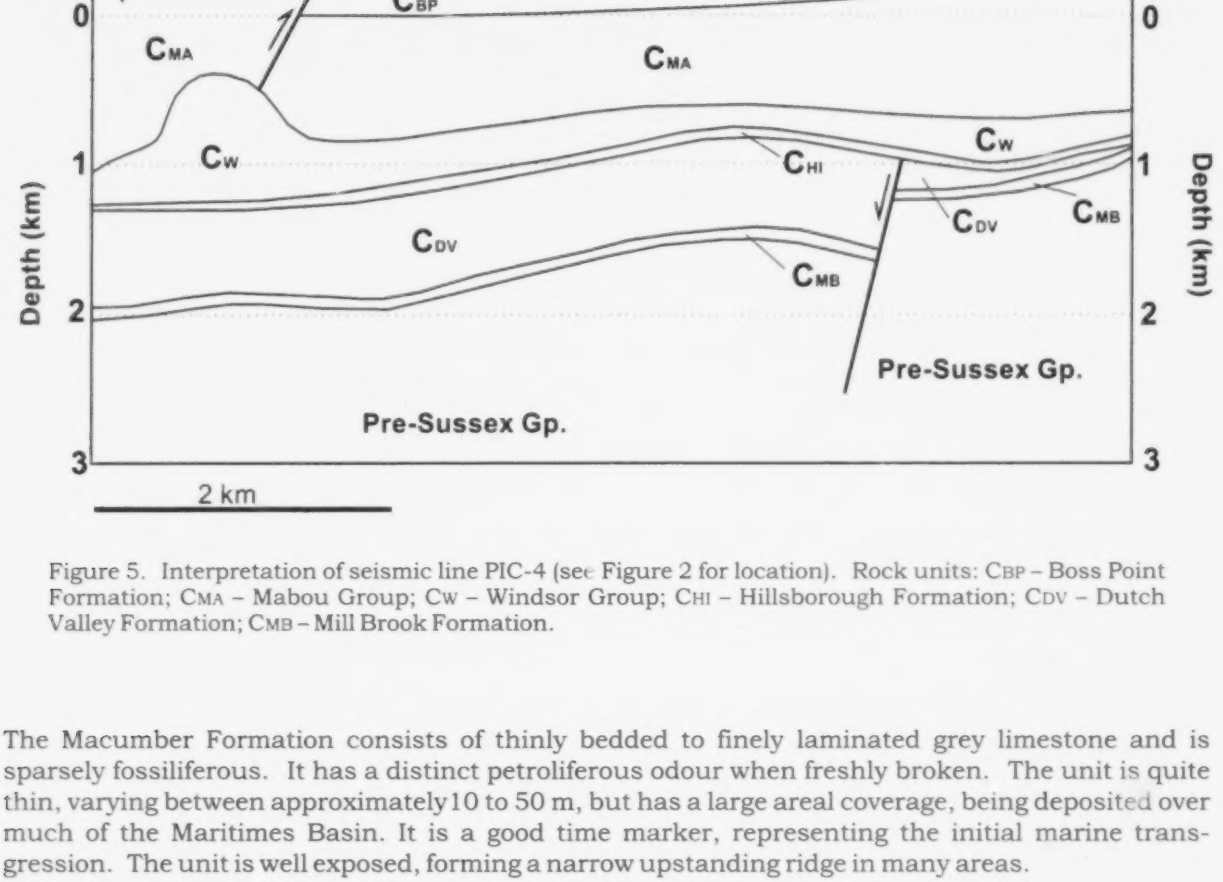

Figure 5. Interpretation of seismic line PIC-4 (see Figure 2 for location). Rock units: CBP – Boss Point Formation; CMA – Mabou Group; CW – Windsor Group; CHI – Hillsborough Formation; CDV – Dutch Valley Formation; CMB – Mill Brook Formation.

The Macumber Formation consists of thinly bedded to finely laminated grey limestone and is sparsely fossiliferous. It has a distinct petroliferous odour when freshly broken. The unit is quite thin, varying between approximately 10 to 50 m, but has a large areal coverage, being deposited over much of the Maritimes Basin. It is a good time marker, representing the initial marine transgression. The unit is well exposed, forming a narrow upstanding ridge in many areas.

The Gays River Formation is, in part, the lateral (landward) equivalent of the Macumber Formation. It consists of laminated to thick-bedded algal limestones and a basal bafflestone.

The Upperton Formation consists of "stratiform, replacive and displacive, nodular to mosaic anhydrite" (McCutcheon 1981). Exposed sections have generally undergone some degree of gypsification. The unit, which is present across much of the basin, is not well exposed. Its surface distribution can be inferred from the presence of karst topography. In boreholes, it tends to be steel blue to dark grey in colour, and fine-grained to cryptocrystalline.

The Cassidy Lake Formation overlies the Upperton Formation and consists largely of rock salt and potash. It does not outcrop, existing only in the subsurface. The Cassidy Lake is the source of potash deposits currently being mined by PCS. The unit has been subdivided into four informal members (Table 2) based on mine and borehole data (Geldsetzer 1978; Kingston and Dickie 1979; Anderle *et al.* 1979; Roulston and Waugh 1985; Howie 1988). The lowermost basal halite member consists of clean to anhydritic coarsely crystalline halite. The overlying middle halite unit consists of argillaceous halite, and is subdivided into a lower grey–green unit and an upper red–brown unit. The middle halite is overlain by the ore zone, which consists of sylvinite grading 10–40% KCl. The ore zone has a basal lower gradational zone consisting of pale orange halite with specks of sylvite that increase in quantity upwards. The highly heterogeneous upper halite unit is the topmost unit of the Cassidy Lake, and has been divided into four subunits. The basal unit ("banded") consists of

broad 10 cm to 1 m thick bands of clean crystalline orange halite, red–purple argillaceous halite, and sylvinitic argillaceous halite. The "sylvinite" unit consists of sylvinite with an average sylvite grade of around 15%. In this unit, carnallite is found in some boreholes, especially towards the northeast of the study area. The "finely laminated" unit consists of deep red–orange clean halite and low-grade sylvinite bands on the order of 5–10 cm thick, separated by millimetre-scale laminae of grey–green clay. It contains numerous borate minerals as scattered platy crystals and spheroidal aggregates (Roulston and Waugh 1981). The topmost "coarse" subunit consists of coarse to very coarse dark grey and orange argillaceous halite. Near the top of the central part of the main salt ridge, dissolution of salt and collapse of overlying rocks have formed solution-collapse breccia, consisting of angular to rounded fragments of anhydrite and green or red mudstone in a green or red muddy matrix. Such breccias are referred to as the "cap rock" in the mine stratigraphy.

In the study area, the Cassidy Lake Formation is overlain by the Clover Hill Formation. The Clover Hill is confined to the subsurface. It consists of a basal dark grey–blue finely crystalline anhydrite unit (referred to as the "upper anhydrite" in the mine stratigraphy) and an upper coarse, dark grey argillaceous halite unit (referred to as "Penobsquis salt").

The upper contact of the Windsor Group is problematic. McCutcheon (1981) noted that the top of the Windsor has a weathered appearance in some areas, concluding that there was a significant hiatus between Windsor and Mabou deposition. Aerial photographs also show an angular discordance between Hillsborough Formation and Mabou Group bedding ridges (McCutcheon 1981). In the basin centre, seismic profiles show that the contact is structurally conformable (Figures 3, 4 and 5), and borehole evidence suggests a gradational contact between argillaceous halite and marine clay of the Clover Hill Formation and mudstone and sandstone of the Mabou Group. At the basin margins, Mabou Group rocks are observed to step across the Windsor Group stratigraphy onto basement (Figure 2). In some areas at the basin margin the contact may be defined by salt welds. A salt weld is defined as "a surface across which now-adjacent strata were originally separated by salt that is now depleted or absent" (Giles and Lawton 1999). The evidence suggests that the Windsor/Mabou contact is unconformable at the basin margins, and conformable in the basin centre.

Mabou Group

In the study area, the Late Viséan to Namurian A Mabou Group comprises a lower fine-grained unit consisting mainly of red mudstone and sandstone, and an upper coarse-grained unit consisting largely of polymictic conglomerate (Anderle *et al.* 1979; McCutcheon 1981). The conglomerates contain clasts derived from basement complex lithologies. The Mabou Group is separated from overlying Cumberland Group rocks by a major unconformity (e.g., Gussow 1953; St. Peter 1992, 1993).

Cumberland and Pictou groups

In the study area, the Cumberland Group consists of yellow–grey sandstones, microconglomerates, quartz-pebble conglomerates and thin coal seams of the Boss Point Formation. The Boss Point outcrops in the east and northeast of the study area, and is of Westphalian A age (Johnson 1995). The Cumberland Group in southeast New Brunswick is paraconformably overlain by the Pictou Group. Fluvial grey sandstone and grey to red mudstone of the Westphalian C-age Salisbury Formation are the only Pictou rocks exposed in the study area.

EVAPORITE STRUCTURE

From study of drill core and seismic reflection profiles, some broad conclusions may be drawn about the structural geology of the Windsor Group evaporites in the study area.

Structural repeats of the evaporite stratigraphy are common. In many cases, the structural repeats are associated with a shallowly to moderately dipping schistosity that is parallel or subparallel to primary layering. These observations are consistent with the presence of recumbent to moderately inclined isoclinal folds. In borehole M-4A (Figure 2), the entire evaporite stratigraphy is observed to be overturned by a large-scale fold. A similar overturned structure is interpreted on seismic line 6 (Figure 3). In some cases, the limbs of these folds are highly attenuated; for example, in borehole D-3 (Figure 2) the middle halite member near the base of the hole is about 55 cm thick. In borehole H-5 (Figure 2), the same unit is more than 30 m thick. The less common presence of steep fabrics within the evaporite section suggests that an overprinting generation of upright folds also exists; this is supported by observations of refolded isoclinal folds in the PCS mine workings.

There is no evidence for significant shearing on steep shear zones within the evaporite section. However, low-angle shearing is present. In some cores that reach or approach the base of the basal halite, mylonites with a shallowly-dipping foliation are present. Examples include boreholes B-3, E-3, E-4A, G-3A, G-4A, N-2, PCS-02-01, PCS-02-02, and PCS-02-04 (see Figure 2 for locations). In the lower 50 m or so of B-3, coarse to very coarse, clean to slightly anhydritic halite gives way to coarse, clean schistose halite. The schistosity becomes more pervasive downward; for example, schistose halite grades downward into coarse-grained halite crystals in a fine-grained schistose matrix, and finally into coarse halite with 10–20° dipping, centimetre-scale bands of fine-grained mylonitic halite over the basal 10 m. The schistosity also becomes shallower downwards over a 50 m interval, from about 45–50° near the top to 10–20° near the base of the Cassidy Lake Formation. The mylonite bands are observed to be asymmetrically folded. The core containing the contact with the underlying Upperton Formation anhydrite is missing; however, according to previous logs (Dickie 1977), the contact is sharp and dips 18–20°. Both the Upperton anhydrite and underlying Macumber Formation limestones contain bands of cataclasite that dip 15–20°. Cores from other boreholes show similar relationships, although with a lesser thickness of mylonitic halite. It appears that there is a significant low-angle, bedding-parallel shear zone lying at the base of the Cassidy Lake Formation. However, it should be noted that such structures are not observed in all holes that intersect the base of the Cassidy Lake Formation, notably PCS-02-03. This is taken as evidence that PCS-02-03 was drilled outside of the area in which dislocation at the base of the Cassidy Lake Formation took place.

Seismic interpretations support salt core observations that there is an important décollement horizon at the base of the Cassidy Lake Formation. While the Upperton, Macumber and Hillsborough formations are little deformed, the overlying Cassidy Lake and Clover Hill formations have flowed into elongate salt walls (Figures 3, 4 and 5). It is unclear whether the salt has penetrated Mabou Group rocks. However, the association of the salt structure with reverse faults in the cover suggests some limited penetration (see below).

At Sussex Corner, Macumber limestone is observed overlying red–grey polymictic conglomerates of the Hillsborough Formation. The limestone is folded in this area (Figure 6), with folds generally plunging moderately to shallowly to the northeast and with near-vertical axial planes. The basal Macumber Formation and underlying Hillsborough Formation are not folded. Therefore, the folds have been interpreted previously as intraformational slump structures (McCutcheon 1981). However, the similarity in orientation and style of the folds and the lack of any evidence for scours at the base of folded units suggest that the folds are tectonic in origin. The style of the folding, that is, upright to inclined folds overlying a basal décollement, is similar to the large-scale folding of Windsor Group salt, as seen in seismic reflection profiles (Figures 3, 4 and 5). Therefore, the folds are

interpreted to be related to décollement tectonics during salt movement, suggesting that the décollement structure is not a simple feature confined to one structural level.

There is also evidence for some structural dislocation along the ore zone. Sylvinite in the ore zone is observed to be highly lineated in some boreholes, with sylvite crystals having aspect ratios of 4:1 and greater. In other boreholes the ore possesses a gneissic fabric, with centimetre-scale interbanding of fine-grained sylvite and blue halite, and clean translucent or light grey halite. In borehole PCS-02-04 (Figure 2), the Upper Halite and Ore Zone members are structurally repeated across a strongly lineated ore section; this deformed ore section is interpreted to represent a northwest-dipping, low-angle ductile shear zone with reverse displacement.

Salt movement appears to be associated with reverse faults in the strata overlying the salt. On line 6 and PIC-4 (Figures 3 and 5), a salt-linked reverse fault is observed to cut the Boss Point Formation. Field evidence for the existence of this fault is seen near the H-28 wellsite (Figure 7). Boss Point Formation rocks are steeply dipping to slightly overturned and facing south, indicating the presence of a reverse-displacement fault to the north of H-28. It is suggested that the elongate nature of the salt body is the result of the structure being associated with a major northeast-trending fault system in the strata overlying the salt. The timing of this faulting and related halotectonism will be discussed in the next section.

FAULT KINEMATICS AND TECTONIC HISTORY

Field evidence and interpretation of seismic reflection profiles have been used to evaluate the kinematic history of individual faults in the study area and thereby establish a tectonic history.

Evidence for the initial opening of the Moncton Subbasin is given by the Gordon Falls Fault. Interpretation of seismic line 2 (figure 4), based on borehole control from PCS/Corridor McCully 1, and the thickness of the Hiram Brook elsewhere in the basin, shows that this roughly east–west-trending fault has a significant thickness of Weldon Formation rocks in its hanging wall. The Weldon Formation is not present in surface exposures to the south of the fault, or in the Kerr-McGee Urney 1 borehole in the footwall (Figures 2 and 4). This implies that the south side of the Gordon Falls Fault was uplifted (i.e., the fault had experienced normal-sense movement) prior to the deposition of Sussex Group rocks.

Albert Formation rocks apparently contain a number of thrust faults and higher-angle reverse structures which do not penetrate the major post-Weldon unconformity. In general, reflectors in Horton Group rocks are undulating and discontinuous in appearance (Figure 4), while reflectors in younger rocks are significantly more continuous and undisturbed in appearance. In the field, it is observed that Albert Formation rocks are more deformed than younger rocks. This is also the case in the Hillsborough area (St. Peter and Johnson 1997; Wilson 2002).

A clear feature in the southeastern part of lines 2 and 6 (Figures 3 and 4) is a northwest-dipping fault of apparent normal displacement, with the Dutch Valley Formation section dramatically thinner to the southeast of the fault. The fault does not cut overlying Windsor Group rocks, and is interpreted to be a Late Tournaisian to Early Viséan normal fault. Dutch Valley Formation reflectors onlap onto the Mill Brook Formation where that unit is folded close to the fault (Figures 3 and 4), suggesting that the structure may have been active as a growth fault during Dutch Valley deposition. Seismic interpretations from the Hillsborough area in the eastern Moncton Subbasin show the Wilson Brook Fault as a similar structure (Wilson 2002). Another possibility is that the fault is a strike-slip fault, with differential movement between rocks below and above the Windsor Group accommodated by flow in the Windsor salt. Such structures were discussed by Jenyon (1986; his figure 2.15). This seems less likely, however, because the Dutch Valley Formation is not particularly

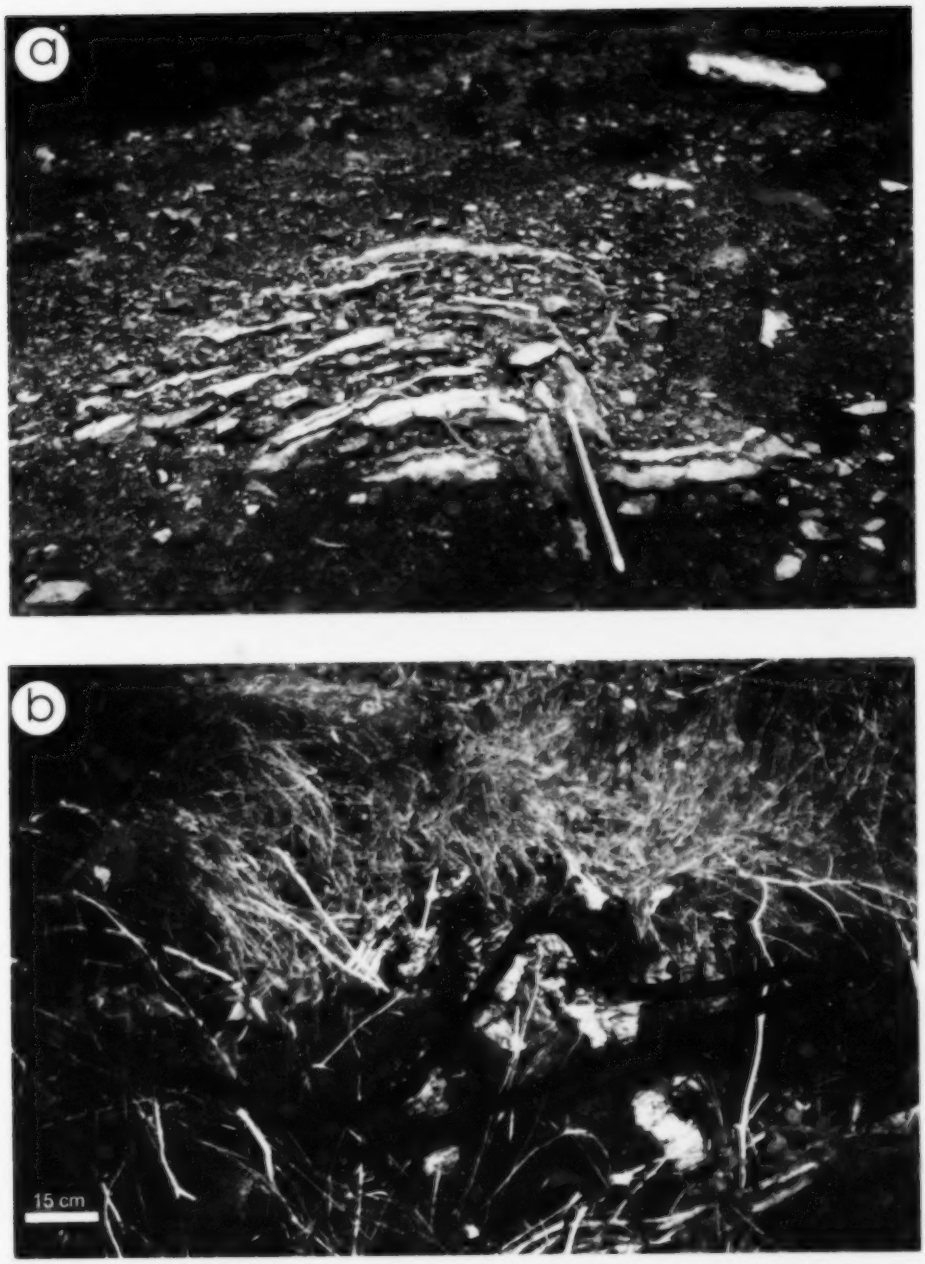

Figure 6. (a) Folded Macumber limestone near the community water well at Sussex Corner. Pencil is 15 cm long. (b) Folded Macumber limestone at Sussex Corner, detached from underlying Macumber limestone which is unfolded.

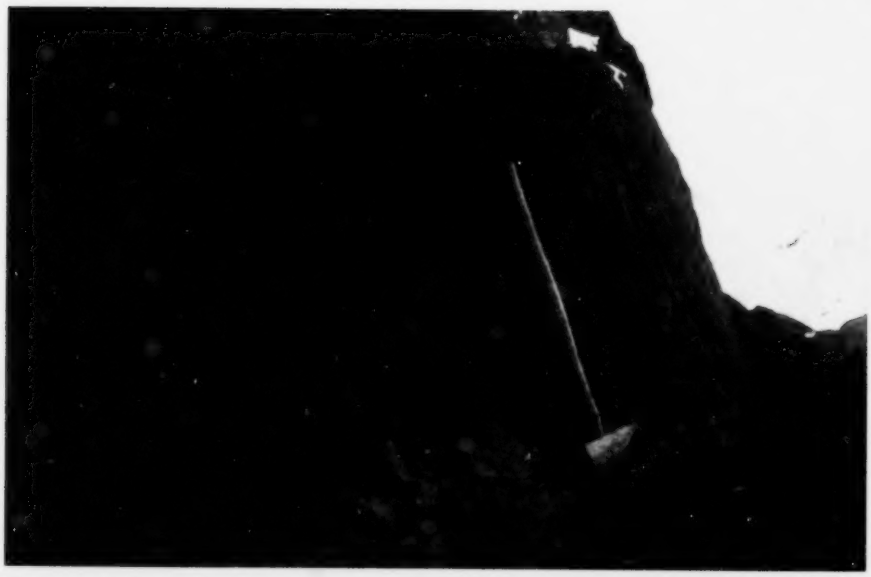

Figure 7. Steeply dipping rippled top surface of Boss Point Formation outcrop near the H-28 wellsite (see Figure 2 for location). Rock hammer is 30 cm in length.

variable in thickness parallel to the fault; hence, strike-slip movements on the fault could not produce the observed thickness difference in the Dutch Valley Formation across the fault.

At the northwest end of lines 2 and 6 (Figures 3 and 4), the seismic interpretations show a wedge of rocks that lies southeast of the Berry Mills Fault and is both underlain and overlain by rocks of the Windsor Group (Macumber and Upperton formations; Figures 3 and 4). Gravity modelling shows that the wedge probably does not consist of salt (Durling and Howells 2002). Previous interpretations have the wedge composed of pre-Windsor Group rocks which have been thrust to the southeast along the Windsor Group rocks (Durling and Howells 2002). Another possibility is that the wedge consists of Mabou Group rocks, and that the overlying Windsor and Mabou rocks have been thrust over the wedge to the northwest. Published maps (e.g., St. Peter 2002) show that Dutch Valley Formation rocks underlie the Macumber at Smiths Creek, favouring the former hypothesis. However, it may be suggested that rocks of the lower Mabou Group and the Dutch Valley Formation have lithological similarities. It may also be argued that the upper contact between rocks in the wedge and overlying Windsor Group rocks is a thrust. Duplex structures imaged in the wedge toe on line 2 (Figure 4) suggest that Windsor and Mabou rocks have overthrust the wedge to the northwest. Reflectors within the wedge are not parallel to the overlying Windsor Group reflectors. The geometry of the Windsor Group above the wedge (Figure 3) can be interpreted as representing a ramp-flat geometry, with a steep interpreted fault through the relatively homogeneous lower Mabou Group rocks, flattening into the contact between upper and lower Mabou Group rocks. However, there is as yet no field evidence to support this interpretation, and further work is required to decide which hypothesis is correct. Whichever hypothesis is correct, the Boss Point Formation cuts down through the Mabou Group northeast of Smiths Creek toward the northwest (Figures 3 and 4), suggesting that the rocks above the wedge were uplifted and eroded prior to Cumberland deposition. Field and seismic evidence reveals a complex system of late contractional structures. The latest movements recorded on the Berry Mills, Gordon Falls, Urney and Clover Hill faults are reverse. These structures all appear to have been long-lived structures that have accommodated numerous phases of movement, but they all show net reverse displacements of Mabou Group rocks. The magnitude of such movements is large, with possibly 2 km of reverse displacement on the Berry

Mills Fault, and approximately 500 m displacement of Windsor Group rocks across the Gordon Falls Fault. The Gordon Falls Fault appears to link at depth with a lower-angle thrust fault (e.g., on line 2, Figure 4), referred to as the Urney fault. The Urney anticline (Figure 2) is interpreted as a fault-termination fold lying above the tip of the Urney Fault. The Urney Fault is exposed to the southwest of the Urney anticline, where the Mill Brook Formation is thrust over the Dutch Valley Formation (Figure 2); the fault dies out to the northeast. The Gordon Falls and Urney faults appear to have been offset by north- to north-northeast-trending faults of sinistral displacement (Figure 2). These may be transfer faults contemporaneous with late thrusting, or may represent a set of later structures. The asymmetry of folds within the salt and the asymmetry of the salt body itself (Figure 3) and the presence of low-angle reverse-sense shearing in the evaporite body (see previous section) suggest that Mabou Group rocks have been thrust to the southeast over the salt, with the deformation distributed across the entire salt body.

The timing of the late contraction has some constraints. As noted above, high-angle reverse structures which accommodate salt movement cut the Boss Point Formation (Figures 3 and 5) and are, therefore, later than Westphalian A in age. Mapping (St. Peter 2002) shows that the Berry Mills fault cuts Pictou Group rocks (Westphalian C), the youngest rocks exposed in the area. Thus it is not possible to definitively constrain the age of late contraction in this area. However, work in the Sydney Subbasin (Gibling *et al.* 2002) suggests that a compressive event (the "Donkin episode") ocurred in late Carboniferous or Permian time. It is suggested that this is the most likely time period for the late contraction associated with halotectonism in the western Moncton Subbasin.

PRELIMINARY CONCLUSIONS

Revisions are required in pre-Windsor Group stratigraphy. The post-Acadian, pre-Windsor section in this area should be divided into two groups. The basal Horton Group comprises Memramcook, Albert and Weldon formations, and is unconformably overlain by the Sussex Group, which consists of the Mill Brook, Dutch Valley and Hillsborough formations.

The structural geology of the evaporite body is complex, with a décollement at the base of the Cassidy Lake Formation, a thrust localised in the ore zone in the southeast, and widely distributed complex isoclinal folding. Halotectonism was associated with a post-Pictou Group contractional event that was probably late Carboniferous or Permian in age.

The tectonic history of the area is interpreted as follows:

1. Basin initiation related to normal displacements on northeast- to east-trending faults concurrent with deposition of the Horton Group .
2. Basin inversion following deposition of Horton Group rocks, resulting in northeast-trending folding and reverse faulting in Horton Group rocks and the formation of the post-Horton unconformity.
3. Renewed extension during and/or after deposition of Sussex Group rocks.
4. Marine transgression, leading to deposition of Windsor Group evaporites.
5. Regional uplift and marine regression, followed by deposition of Mabou Group rocks.
6. Emplacement of the wedge structure associated with the Berry Mills Fault (Figures 3 and 4) prior to Cumberland Group deposition.
7. Basin inversion following deposition of the Boss Point and Salisbury formations, and localized in part within the Windsor salt. This basin inversion resulted in reverse movement on the Gordon Falls, Berry Mills, Urney and Clover Hill faults and reverse movements on faults confined to the cover rocks above the salt. This period of contraction may correspond to the Donkin episode of probable late Carboniferous or Permian age (Gibling *et al.* 2002).

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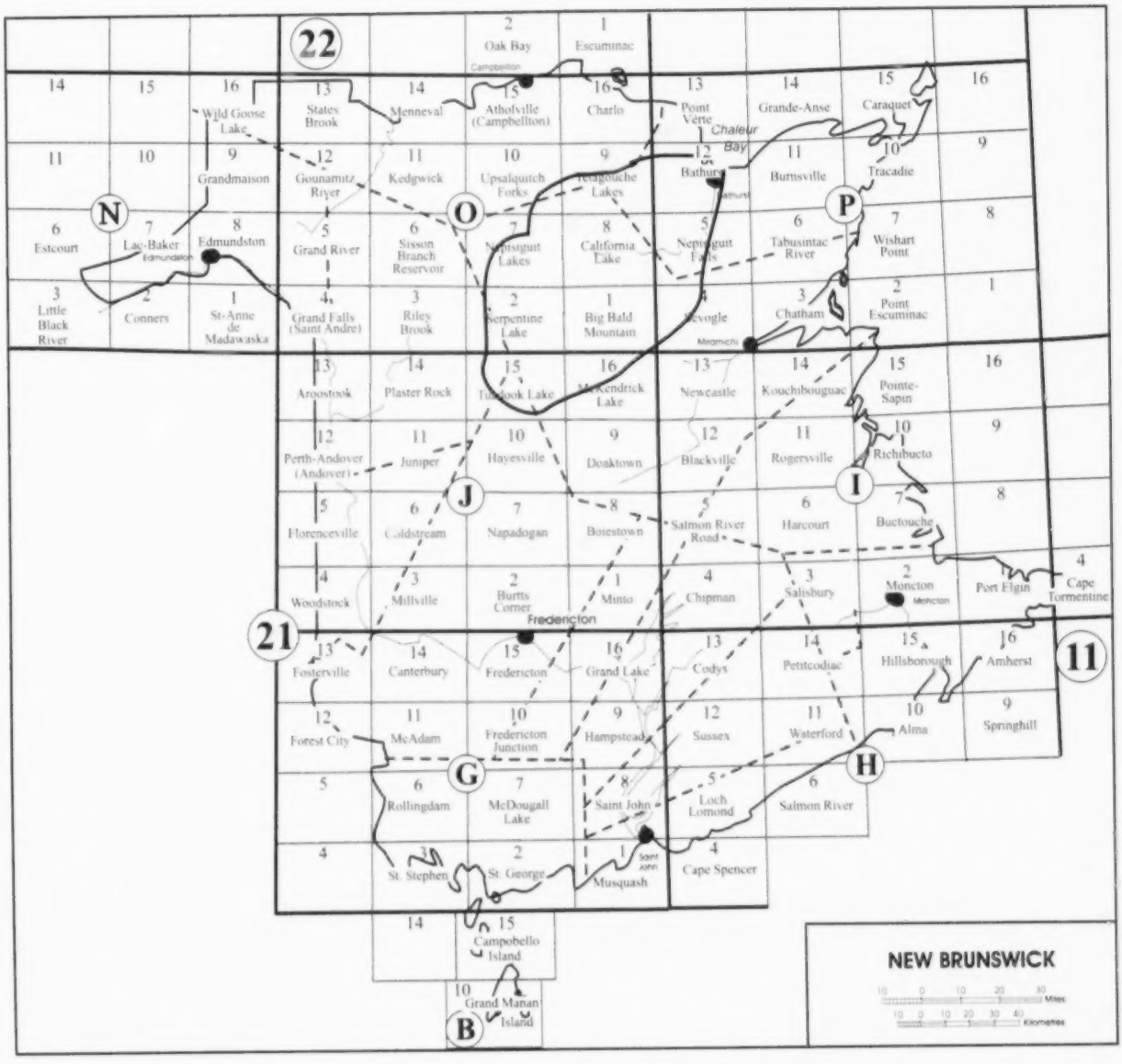

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Conversion Factors:
Imperial and International System of Units (SI)

The following multipliers should be used to convert imperial units to SI units or SI units to imperial units:

CONVERSION FROM SI TO IMPERIAL			CONVERSION FROM IMPERIAL TO SI		
SI Unit	*Multiply by*	*Gives*	*Imperial Unit*	*Multiply by*	*Gives*
			LENGTH		
1 mm	0.039 37	inches	1 inch	**25.4**	mm
1 cm	0.393 70	inches	1 inch	**2.54**	cm
1 m	3.280 84	feet	1 foot	**0.304 8**	m
1 m	0.049 709 7	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	**1.609 344**	km
			AREA		
1 cm^2	0.155 0	square inches	1 square inch	**6.451 6**	cm^2
1 m^2	10.763 9	square feet	1 square foot	**0.092 903 04**	m^2
1 km^2	0.386 10	square miles	1 square mile	2.589 988	km^2
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
			VOLUME		
1 cm^3	0.061 02	cubic inches	1 cubic inch	**16.387 064**	cm^3
1 m^3	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m^3
1 m^3	1.308 0	cubic yards	1 cubic yard	0.764 555	m^3
			CAPACITY		
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	**4.546 090**	L
			MASS		
1 g	0.035 273 96	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.32 150 75	ounces (troy)	1 ounce (troy)	**31.103 476 8**	g
1 kg	2.204 62	pounds (avdp)	1 pound (avdp)	**0.453 592 37**	kg
1 kg	0.001 102 3	tons (short)	1 ton (short)	**907.184 74**	kg
1 t	1.102 311	tons (short)	1 ton (short)	**0.907 184 74**	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	**1016.046 908 8**	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	**1.016 046 908 8**	t
			CONCENTRATION		
1 g/t	0.029 166 6	ounce (troy)/ ton (short)	1 ounce (troy)/ ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights/ ton (short)	1 pennyweight/ ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

1 ounce (troy)/ton (short)	20.0	pennyweights/ton (short)
1 pennyweight/ton (short)	0.05	ounce (troy)/ton (short)

NOTE: Conversion factors in bold type are exact.

SOURCE: Metric Practice Guide for the Canadian Mining and Metallurgical Industries, published by The Mining Association of Canada in cooperation with the Coal Association of Canada.